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Changes in the mountain river discharge in the northern Tien Shan since the mid-20th Century: Results from the analysis of a homogeneous daily streamflow data set from seven catchments

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ABSTRACT

This study is an assessment of the changes in seasonal and monthly flow in seven catchments draining the northern Tien Shan Mountains in Central Asia over a period from the 1950s to the present day. The purpose is to provide a first assessment of the flow response to climate change in regionally important catchments given their contribution to the water resource. All the catchments have a natural flow regime, and are therefore sensitive to climate change, but differ in area, elevation and glacial extent. Trends in flow were characterised using the Mann-Kendall test for standard meteorological seasons and individual months for mean flow, five flow quantiles and peak-over-threshold series for the period 1974–2013 at all sites and from the 1950s where data were available. The results were related to trends in seasonal temperature and precipitation from the regional high-elevation meteorological stations and glacier mass balance, equilibrium line altitude (ELA) and accumulation area ratio (AAR) records from the Tuyuksu glacier. The results show no reduction in streamflow in any catchment or season in the northern Tien Shan since the 1950s. Positive trends in all flow indicators, including peak-over-threshold frequency, were observed in catchments with higher glacierization of over 10% and extensive presence of rock glaciers and permafrost indicating increased melt over the period which is characterised by a long-term increase in temperature. These trends were most evident in autumn and winter. In catchments with low glacierization, variability in summer flow was controlled primarily by precipitation of the preceding cold season. Correlation with glacier mass balance was weak but changes in ELA and AAR indicate that production of liquid runoff at higher elevations contributes to increased streamflow partly compensating for the declining glacier area. The observed changes in streamflow do not suggest any immediate problems with water availability in the northern Tien Shan. On the contrary, increased autumn and winter flows point at a more prolonged recharge of reservoirs and aquifers though eventually this water source will be exhausted.

1. Introduction

The rivers of Central Asia, most of which start in the mountains, supply up to 90% of water required for domestic, industrial and agricultural use on the plains, which are characterised by arid and semi-arid climate (Viviroli and Weingartner, 2004). Peaking in the growing season between May and September, runoff from the mountains is used for irrigating agricultural land, from the industrial-scale cotton production in the Aral Sea basin (Micklin, 2007) to the smaller-scale commercial and subsistence farms in Central Asia and north-western China (Braun et al., 2009). Many rivers cross national boundaries and thus changes in discharge, either natural or due to the growing water abstraction and construction of dams and reservoirs, have become an issue of high economic and political importance which is likely to grow with time in line with the observed and predicted population growth (Siegfried et al., 2011; Reyer et al., 2015).

The cryosphere, including the seasonal snow pack, glacier ice, rock glaciers and permafrost, nourishes these rivers and is the main

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contributor to runoff. The estimations of the cryosphere's total contribution and of the shares contributed by its components vary between regions, elevation bands and seasons as well as methods of assessment, but most studies suggest that runoff from the glacierized surfaces contributes as much as 40–80% of total runoff in the summer months (Hagg et al., 2006; Unger-Shayesteh et al., 2013; Duethmann et al., 2015). Kaser et al. (2010) developed a population impact index to quantify the potential human dependence on glacier melt in 18 large river catchments around the world and found that its value is highest in Central Asia.

The dependence of runoff on the state of the cryosphere makes water resources in Central Asia potentially vulnerable to climate change. There is strong evidence for impacts of climatic warming on the extent of glaciers which are losing their area throughout the region (Kutuzov and Shahgedanova, 2009; Narama et al., 2010; Sorg et al., 2012) at a rate reaching 1% a^{-1} in the northern Tien Shan (Severskiy et al., 2016). Rock glaciers are an important source of water in Central Asia (Bolch and Marchenko, 2006) and acceleration of their movement, which may be attributed to climatic warming (Kääb et al., 2007), has been reported in the region as well as a reduction in the area occupied by permafrost, an increase in temperature of the permafrost and depth of the active layer (Marchenko et al., 2007).

From the perspective of water resources, it is important to know to which extent changes in the cryosphere and, importantly, its components (e.g. glacier and/or ground ice versus seasonal snow pack) affect discharge at present and will affect it in the future (Lutz et al., 2013; Unger-Shayesteh et al., 2013). These impacts depend on the glacierization of catchments (including rock glaciers) and extent of permafrost, amount and seasonality of precipitation and characteristics of soil cover, all of which are a function of altitude of the catchments. The attribution of the observed trends is complicated by the combined multifarious influence of temperature and precipitation including seasonal snow storage, elevation-dependent changes in the onset and duration of melt season, timing of transition between solid and liquid precipitation and soil freezing (Birsan et al., 2005; Kormann et al., 2015). Thus Duethmann et al. (2015) detected positive trends in discharge in the Kakshaal and Sari-Djaz catchments with 4% and 21% glacier cover during the 1957–2004 period, estimating that glacier melt contributed 9–24% and 35–48% of the total increase in discharge respectively. Kriegel et al. (2013) assessed changes in mean monthly discharge in the Big Naryn and Small Naryn catchments with glacierization of 10% and 12% respectively but did not detect significant changes in August (when glacier melt signal is strongest) in the former, and found negative trends in the latter. Krysanova et al. (2015) and Kundzewicz et al. (2015) reported positive trends in discharge in the Aksu catchment (Kyrgyzstan/China) and highlighted varying importance of precipitation and glacier melt (approximated by temperature) as sources of increasing flow.

Regional climate scenarios suggest that the observed warming will continue into the 21st Century in Central Asia (Schiemann et al., 2008; Lutz et al., 2013; Mannig et al., 2013; Shahgedanova et al., 2016) contributing to glacier wastage and permafrost degradation. There is no consensus between the models on the direction and magnitude of trends in precipitation in Central Asia, however, neither model projects an increase in precipitation which might be strong enough to reverse the observed loss of glacier ice. Most modelling studies, focusing on future discharge, suggest that in response to the observed shrinkage of glaciers, initial growth will occur followed by a decline, the extent and timing of which depend on glacierization of catchments and the total amount, seasonality and projected changes in precipitation (Hagg et al., 2006; Chen et al., 2017). Hydrological models, applied in glacierized catchments of Central Asia to date, do not parametrise permafrost and rock glaciers (although they include debris-covered ice) and this is another source of uncertainty affecting hydrological projections (Chen et al., 2017).

The following questions are critical to water management in Central Asia: (i) What are the observed and projected trends in seasonal flow in undisturbed catchments particularly in summer when the need for irrigation is highest? (ii) What are the observed and projected trends in various flow indicators relevant to both water and hazard management? (iii) What is the relative importance of different drivers in the overall change in discharge in catchments with different attributes? (iv) When will the peak flow in the snow- and ice-nourished rivers occur and if and when will discharge decline?

A persistent problem constraining the detection and attribution of climate-driven hydrological change in Central Asia, using both observational and modelling approaches, is a lack of the long-term, homogeneous and continuing measurements of streamflow in undisturbed catchments with diverse topographic, climatic and glaciological conditions (Braun et al., 2009; Sorg et al., 2012, Unger-Shayesteh et al., 2013; Chen et al., 2017). As a result of the limited data availability, most assessments of the observed changes in discharge focus on mean annual, seasonal and monthly flow in a small number of catchments (e.g. Kriegel et al., 2013; Krysanova et al., 2015; Kundzewicz et al., 2015; Duethmann et al., 2015). Very few studies investigate changes across larger regions (e.g. Aizen et al., 1997; 2000; Hagg et al., 2006).

A lack of assessment of data quality is another issue which hinders the detection of hydrological change (Unger-Shayesteh et al., 2013; Chen et al., 2017). The majority of rivers in Central Asia are managed through water abstraction, construction of dams and modification of channels. Rivers with natural flow are affected by natural disturbances, altering channels and forcing repositioning of gauges, in particular by debris flows which were especially frequent in the 1970s (Kapitsa et al., 2017). While this information is collected together with flow measurements by dedicated national agencies, it is not easily available to researchers and most studies either use hydrological data at face value, acknowledge the absence of such information, or select catchments whereby water abstraction is unlikely due to their high elevation (e.g. Kriegel et al. 2013).

This paper has two objectives. Firstly, it presents a long-term (1950 onwards), [near] homogeneous data set of daily streamflow for seven catchments with diverse characteristics in the Balkhash-Alakol basin, south-eastern Kazakhstan encompassing the northern Tien Shan and the adjacent plains (Fig. 1). Secondly, it characterises changes in seasonal and monthly streamflow using a full range of flow indicators derived from daily streamflow values and examines these variations in the context of the observed climatic fluctuations, glaciological and cryolithological change.

In contrast to other studies, which focus on larger rivers, relatively small rivers have been selected because their flow is not modified (down to the gauging sites used in this study) and because hundreds of small rivers across the region provide water for human use. We envisage that the presented data will initiate the development of a reference hydrological data set for the mountains of Central Asia which can be used for the detection and attribution of trends and in modelling studies.

2. Data

2.1. Hydrological monitoring and the available data

Systematic hydrological monitoring began in the former Soviet Central Asia at the start of the 20th Century and became more widespread in the 1950s. The number of gauging stations peaked in the 1980s across the region when, in the Balkhash-Alakol basin alone, there were over 180 gauging sites covering a full range of topographic conditions and biomes from the nival zone to semi-deserts. The collected data were processed by the National Hydrometeorological Centre of Kazakhstan (KazHydroMet) and published annually in analogue format as the Annual Data on Water Regime and Resources Reports (ADWRR, 2014 and earlier issues) which were available from scientific libraries

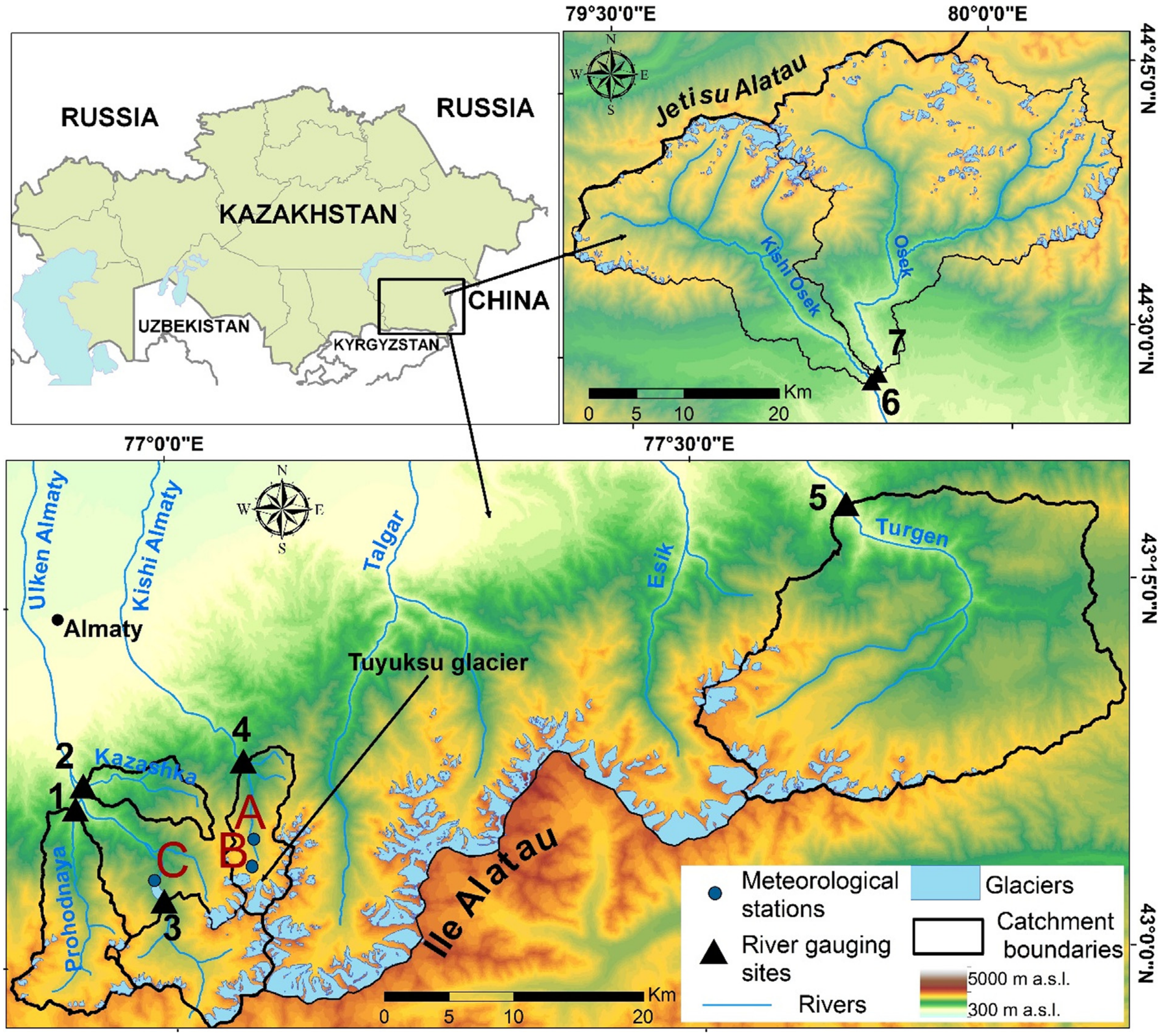

Fig. 1. Study area. Numbers show locations of the gauging sites (Table 1): 1 – Prohodnaya, 2 – Teresbutak, 3 – Ulken Almaty, 4 – Kishi Almaty, 5 – Turgen, 6 – Osek, 7 – Kishi Osek. Letters show locations of meteorological stations: A – Mynzhilki, B – Tuyuksu, C – Bolshoe Almatinskoe Lake (BAL).

and archives. Following the collapse of the Soviet Union, the number of gauging sites declined in the 1990s across the region. In the Balkhash-Alakol basin, there were only 22 sites located mostly on the plains. In the 2000s, Kazakhstan invested in the restoration and expansion of the monitoring network, increasing the number of gauges to 62. However, the data are provided on a commercial footing which restricts their use by the research community.

On the rivers of the Balkhash-Alakol basin (as well as in all other countries of the post-Soviet Central Asia), water stage is measured in open channels twice a day, at 8:00 and 20:00 local time. Simultaneous current metering at a range of points along a river cross-section is conducted at least every 10 days near the gauging sites when there are no significant changes in water stage. Whenever stage is changing on the day-to-day basis (particularly when it is increasing), direct current metering is conducted daily and reported to KazHydroMet in real time. Streamflow values are calculated from the rating curves which are updated using simultaneous stage and streamflow measurements, thus reducing uncertainty associated with changes in reference hydraulic regime (Le Coz, 2012).

The daily means of both stage and streamflow are published in the ADWRR (2014 and earlier issues). In addition, metadata on each site are presented: information on the condition of sites in a given year, meteorological and other natural events which can affect discharge, such as ice formation, dates of floods, debris flows or landslides, and their impacts on the channels. Repositioning of sites, changes in measurement practices, authorised water abstraction, and construction of dams are reported. Indirect effects of human activities, resulting from changes in land use (except urbanisation), and groundwater abstraction are not reported. Typically, the low-elevation sections of catchments experience stronger human modifications while the high-elevation sections are more frequently affected by natural hazards.

2.2. Selection of gauging sites and preparation of the data set

In this study, discharge records for the Balkhash-Alakol basin starting in the 1950s were used. Annual issues of the ADWRR (2014 and earlier issues) were obtained from the KazHydroMet archive and digitised to present data in electronic numerical format. The unique site certificates issued by KazHydroMet, describing site characteristics, changes to its surroundings and observational practices were used. To select gauging sites with reliable data, which would be comparable in quality to the data supplied by other reference networks (Whitfield et al., 2012), the following criteria were applied: (i) suitable length and continuity of records; (ii) absence of human disturbances, including water abstraction, construction of the upstream dams, reservoirs and modifications of channels; (iii) homogeneity of measurements including

the absence of changes of gauge locations, natural disturbances resulting in step changes in flow measurements, and land use in the upstream catchment. High-resolution satellite imagery (Landsat, ASTER and imagery available from Google Earth) was inspected for changes in land cover and location of water abstraction channels and, for several sites, this was complemented by field surveys.

The low signal-to-noise ratio in hydrological time series implies that the length of hydrological records should be sufficient to detect long-term climate-related trends as opposed to the short-term trends arising from climatic variability (Wilby, 2006). The duration of the time series appropriate for the detection of the climate-related trends is debated. Kundzewicz and Robson (2004) recommend that hydrological series which are at least 50 years long should be used; Hannaford and Buys (2012) and Whitfield et al. (2012) recommend 40-year records and Birsan et al. (2005) and Kormann et al. (2015) recommend 30-year records for analysis of climate-driven trends in runoff. In Central Asia, the selection of assessment period is further complicated by changes in temperature and precipitation which occurred in the 1970s in response to changes in atmospheric circulation in the Pacific (Cao, 1998).

Continuing discharge records exceeding 50 years are available in the Balkhash-Alakol basin, e.g. at the rivers Ile and Osek, measurements started in 1910 and 1913 respectively (Piven, 2011). However, most long records are unusable either because river flow was modified (e.g. the Ile) or because the assessment of data quality is impossible prior to 1950 (e.g. the Osek). A gap in measurements, which affected all national hydrological networks in Central Asia in the 1990s, negatively affects but does not invalidate the continuing records. Following Hannaford and Buys (2012) and Whitfield et al. (2012), we adopted a trade-off between the availability of reliable data and record length setting the minimum record length to 40 years. The missing data threshold was set to 10 years in order to retain data from the sites which did not operate between 1998 and 2006. We did not infill the gaps (mostly because longer gaps occur across the region simultaneously) although a variety of methods of data infilling is available (Harvey et al., 2012) and can be applied in the future using, for example, modelled data.

A total of seven sites satisfying the above criteria were selected (Fig. 1; Table 1). For three rivers (the Ulken Almaty, Turgen and Teresbutak) 60-year records were available. For the selected sites, the metadata were examined and records of relevant events, changes and problems with data quality were made. Field surveys and interviews with observers were conducted in the Ile Alatau catchments to clarify spurious comments in the ADWRR (2014 and earlier issues) and in the site certificates. In addition, sites satisfying the data quality but not the length and continuity criteria have been identified for use either as donor stations for data verification or in modelling studies where shorter records are sufficient.

Following digitisation, the daily streamflow database for the selected seven sites was examined for potential errors independently by two operators. The typical sources or errors in streamflow data are entries of erroneous measurements, misprints in the analogue copies and incorrect entry of digital data from the scanned pages of the aged manuscripts (Brönnimann et al., 2006). Where entries were identified as spurious, hydrological records from other sites and meteorological records were examined and a decision was made on whether to retain the reading or replace by an average of the neighbouring readings (overall, a very small number of readings were replaced).

2.3. Characteristics of the selected hydrometric records

All sites are positioned in the lower and middle mountains in the Ile (Zailiiskiy) Alatau, which has a higher density of measurements, and in the Jetisu (Djungarskiy) Alatau (Table 1, Fig. 1). In both regions, the selected catchments are located close to each other but never along the same river. In particular, the Prohodnaya and Teresbutak are sub-catchments of the wider Ulken Almaty catchment extending to the plain. However, they do not belong to its high-elevation sector, which is considered in this study, and located upstream of the Prohodnaya and Teresbutak sites (Fig. 1). The Kishi Osek is a tributary to the Osek, however, the Osek site is located upstream of the confluence of the two rivers. Size, elevation span and glacierization of the selected catchments are different predetermining different responses of streamflow to climate change and variability despite their spatial proximity (Kriegel et al., 2013; Duethmann et al., 2015; Kormann et al., 2015).

In this study, we defined catchment area by limiting its lowest boundaries to the elevation of the streamflow gauging site. In the case of the Teresbutak, Prohodnaya and Kishi Osek (Table 1; Fig. 1), the gauging sites are positioned at or very close to the rivers' mouth and the whole catchments are included. In the case of the Osek and Turgen, the gauging sites are positioned in the foothills and, therefore, only high- and middle-elevation sectors of the catchments, which extend further onto the plain, are considered. In case of the Kishi Almaty and Ulken Almaty, gauging sites are located at higher elevations (Table 1) and represent higher-altitude sectors of the upland watersheds. These definitions of catchment boundaries affected calculation of glacierization (Tables 1 and 2; Sect. 3) which is defined as a percentage of catchment area occupied by glaciers and is related to the elevations of the catchments (maximum elevations of all catchments are close) and of streamflow gauging sites, which vary by 1000–1400 m (Table 1). Thus glacierization of the Ulken Almaty and Kishi Almaty catchments is higher than that of the Turgen, Osek and Kishi Osek catchments although the absolute values of glacierized areas in the latter three

Table 1
Characteristics of the study catchments. Catchment areas are calculated to the locations of the gauging sites which represent minimum elevation in the catchment. Gauging site locations (Fig. 1) and names of the rivers used prior to 1990 are shown in parentheses. Glacierized areas refer to 2008 and 2011 (Table 2). *BAL is Bolshoe Almatinskoe Lake (Fig. 1).

River	Site name, coordinates (°N; °E)	Start year	Missing data		Gauged area			Catchment elevation (m a.s.l.)		
			Years	% all data	Total	Glacierized		Min	Max	Mean
					km²	km²	%			
Prohodnaya (1)	Mouth; 43.1010; 76.911	1965	2011	2.1	82	3.3	4.0	1442	4180	2820
Teresbutak – Kazashka (2)	Mouth of Kazashka; 43.1244; 76.9153	1953	2003	0.6	31	0	0	1389	2830	2370
Ulken Almaty (Bolshaya Almatinka) (3)	1.1. km upstream BAL*; 43.0389; 76.9947	1952	1994, 1996, 1998, 1999	3.9	74	11.4	15.4	2556	4355	3420
Kishi Almaty (Malaya Almatinka) (4)	Below mouth of Sarysai; 43.1396; 77.0684	1974	1998, 1999, 2000, 2003	4.1	47	5.6	11.9	1940	4340	3120
Turgen (5)	Tauturen village; 43.1385; 77.6501	1950	1998–2000	4.7	548	20.5	3.7	1142	4390	2800
Kishi Osek (Malyi Usek) (6)	0.2 km upstream from mouth; 44.460; 79.8187	1961	1999–2005	15.3	418	24.6	5.9	1234	4210	2720
Osek (Usek) (7)	1.7 km upstream confluence with Kishi Osek, 44.5735; 79.8684	1961	1998–2006	17.1	711	31.7	4.5	1265	4160	2700

Table 2
The extent of and changes in the glacierized area in the study catchments (Kokarev and Shesterova, 2011, 2014). Glacier change is calculated for the period starting 1955/56.

Catchment/year	Glacierized area (km^2)						Area reduction	
	1955/6	1970	1974	1990	2008	2011	km^2	%
Ulken Almaty	21.8	–	16.6	13.6	11.4	–	10.4	47.7
Prohodnaya	–	–	6.8	4.2	3.3	–	–	–
Kishi Almaty	9.3	–	7.4	6.6	5.6	–	3.7	39.8
Turgen	35.7		31.0	25.5	20.5	–	15.2	42.6
Kishi Osek	38.2	34.5	–	29.6	–	24.6	13.6	35.6
Osek	64.8	54.7	–	41.6	–	31.7	33.1	51.1

catchments are larger (Tables 1 and 2). Therefore, comparisons of changes observed in different catchments are, to a significant extent, comparisons of changes which occur at different elevations.

There was no significant land cover change in the catchments except the ongoing de-glacierization (Table 2). However, multiple natural disturbances occurred. In the Kishi Almaty, the debris flow of 1973 significantly modified the river channel invalidating comparisons with the earlier record. Therefore, measurements starting in 1974 were used, following the assessment by KazHydroMet. A dam, designed to prevent mudflows, is located in the headwaters of the Kishi Almaty, however, it does not change water residence time and flow continues in the natural channel downstream. The Ulken Almaty site was destroyed by the debris flow in 1994 but rebuilt at distance of approximately 800 m upstream from the earlier location. The difference in altitude between the two locations is approximately 30 m and there is no surface water influx at this stretch of the river. KazHydroMet recommended continuation of the record. Our inspection of the time series did not reveal any step changes in the data before and after the site relocation and the full record was used. According to the ADWRR (2014 and earlier issues), fewer direct measurements of very high flow were conducted on the Ulken Almaty after 1994 increasing the uncertainty. The hydrological observer, operating the site since the 1990s, did not confirm this conclusion (S. Subbotin, Pers. Com., August 2016). The occurrences of smaller-scale floods and debris flows on all other rivers were noted, however, as no step changes in the time series were detected, the records were deemed usable.

It is suggested in the ADWRR (2014 and earlier issues) that uncertainty in stage measurements is higher at the Prohodnaya gauge than elsewhere because the river has a braided channel making its record unsuitable for the assessment of long-term trends. Our inspection of the river channel did not reveal any braiding that was stronger than in the other catchments and none at the gauging site and the record was retained. Although the Teresbutak gauge has always been referred to as located on the Teresbutak River in the ADWRR (2014 and earlier issues), it is in fact located at the mouth of the River Kazashka to which the Teresbutak is a tributary. We use the historical name of Teresbutak.

2.4. Meteorological and glaciological data

Monthly data from three high-elevation meteorological stations in the Ile Alatau - Bolshoe Almatinskoe Lake (BAL; 2500 m a.s.l.) in the Ulken Almaty catchment; Mynzhilki (3010 m a.s.l.) and Tuyuksu (3438 m a.s.l.) in the Kishi Almaty catchment – were used (Fig. 1). In the Jetisu Alatau, there are no stations with long-term, continuous records located close to the streamflow gauging sites.

Glacier inventories have been conducted in the Ile and Jetisu Alatau at regular intervals since the 1950s (Kokarev and Shesterova, 2011, 2014; Severskiy et al., 2016). Data on the glacierized areas were obtained from these inventories (Table 2).

Measurements of mass balance using the glaciological (stake) method, equilibrium line altitude (ELA) and accumulation area ratio (AAR) have been conducted at the Tuyuksu glacier (the source of the Kishi Almaty) and reported to the World Glacier Monitoring Service (WGMS) since 1957 by the Kazakhstan Institute of Geography. It was previously shown that changes in the area and volume of the Tuyuksu glacier correlated strongly with changes in glaciers of the Ile Alatau as a whole (Severskiy et al., 2016).

Winter and summer mass balance time series were used. Winter mass balance represents maximum snow accumulation at the end of the accumulation season and refers to the periods between the onset of negative daily mean temperatures (beginning of September to mid-October) and transition to the positive daily mean temperatures (May–early June) at the Tuyuksu station. Summer balance, referring to the periods between the onset of positive and negative daily mean temperatures, represents melt, which can be interrupted by snowfalls due to the summer peak in precipitation typical of the high-elevation zone of Central Asia (Dyurgerov et al., 1994).

Catchment elevations (Table 1) were derived from the void-filled SRTM3 GDEM with 30 m resolution (https://lta.cr.usgs.gov/SRTM1Arc).

3. Methodology

The daily streamflow data were transformed into time series for individual months (mean flow only) and standard meteorological seasons using a variety of hydrological indicators characterising the whole flow range. The flow indicators time series examined for (i) long-term trends in flow; (ii) short-term oscillations which can be attributed to decadal climatic variability; (iii) shifts in seasonality; and (iv) changes in extreme flow values with emphasis on the high flow in summer. These time series were examined for a fixed period of 1974–2013 to accommodate the best-instrumented Kishi Almaty catchment, which extends into the Almaty city with over 1.5 million population, and to enable comparison between the catchments. The magnitude and significance of trends are often sensitive to the start and end points of a study period (Unger-Shayesteh et al., 2013). We stress than unlike 1972, when strong negative anomalies in mean annual temperature were registered in Central Asia and 1973, when positive temperature anomalies were registered in the Issyk-Kul basin (Gieze et al., 2007) and to a lesser extent in the study region (Fig. 11 further in the text), no significant anomalies in precipitation and temperature were observed in 1974 with an exception of DJF temperature which was the fifth lowest in the 1950–2013 record from the Mynzhilki station. In order to utilise the full range of data extending to the 1950s and assess the sensitivity of trends to changes in atmospheric circulation in the 1970s, which affected the study region (Cao, 1998), the same analyses were repeated for rivers other than the Kishi Almaty for the full duration of their records.

To characterise streamflow at the selected sites, descriptive statistics including mean, coefficient of variation (CV) and thresholds Qn indicative of flow exceedance n % of the time were used including Q90, Q70, Q50 (median), Q30 and Q10. We note that Q90 (flow which was equalled or exceeded for 90% of the specified term) and Q10 (flow which was equalled or exceeded for 10% of the specified term) are indicators of low and high flow respectively. Q95 and Q5 were excluded because of stronger uncertainties associated with measurements of very low flow in DJF and very high flow in JJA as suggested by the ADWRR (2014 and earlier issues). Decadal hydrographs of daily mean streamflow were calculated starting in 1950 (or later when record began) for each site. Although these analyses may be sensitive to individual flood events as well as gaps in the data, they illustrate shifts in seasonality and provide information on decadal variability in streamflow. In this paper, numerical metrics characterising time shifts in peak flow or spring freshet were not used because the frequently employed metrics (such as date of annual peak flow and centre of volume) are not sufficiently robust (Dery et al., 2009; Whitfield, 2013) while application of the more advanced methods (e.g. Dery et al., 2009; Kormann et al.,

2015) warrants a separate publication.

To examine the long-term changes, Q*n* were calculated for each year and each season, e.g. from DJF 1951 to SON 2013, following Hannaford and Buys (2012) and Hannaford (2015). The two-sided Mann-Kendall test (Kendall, 1975) was applied to the seasonal time series of each flow indicator and meteorological variables to examine the data for the presence, magnitude, and statistical significance of monotonic trends. Prior to the application of the Mann-Kendall test, serial correlation was removed using a trend free pre-whitening procedure (Yue et al., 2002). Trend magnitude was characterised by fitting the Sen's slope estimator (Sen, 1968) to each time series and expressed as percentage change per year of the 1974–2013 (or full record) mean value of the given indicator. Statistical significance was set at 5% confidence level.

The moving window technique was used to evaluate changes over shorter (i.e. 20-year) time periods characterising the influence of climatic variability on hydrological trends (Wilby, 2006; Hannaford and Buys, 2012). This assessment was not applied to the Osek and Kishi Osek flow time series because of the comparatively large amount of missing data (Table 1).

In the glacierized catchments, the occurrence of streamflow exceeding Q10 threshold may result either from precipitation input or from the enhanced melt. Storm events tend to result in a short-term increase in streamflow (i.e. flash floods), while enhanced melt leads to a longer sequence of days with high streamflow values (e.g. 1–2 weeks of the highest streamflow values at the peak of the melt season). The use of Q10 statistics, therefore, may result in a loss of data on the secondary short-term peaks in streamflow resulting from intensive rainfall (Bača and Bačová Mitková, 2007). This problem can be avoided if peak-over-threshold (POT) method is used whereby independent peaks above a certain threshold are considered (Black and Burns, 2002). POT records were constructed for the Ulken Almaty and Turgen rivers using thresholds giving on average 3.0 exceedances per year for the 1950–2013 time period and analysed for trends in temporal distribution of POT events. Other rivers with larger catchments were not considered because of the missing data.

Pearson correlation between the streamflow time series and meteorological variables, winter and summer components of mass balance was calculated using the original and de-trended time series from the concurrent seasons and with a time lag (meteorological variables leading streamflow) for the entire period of observations and for the 20-year moving windows. The time series of seasonal temperature and precipitation from all three meteorological stations were used but results for the Mynzhilki station are shown as its records showed the highest correlation with river flow. These analyses were not performed for the Osek and the Kishi Osek because of the lack of suitable meteorological data.

4. Characteristics of the selected catchments

The region is characterised by strong seasonal variations in temperature and precipitation (Fig. 2). The westerly flow dominates in autumn and spring resulting in the precipitation maxima in April–May on the plains shifting towards May–July in the middle and high mountains, where snow accumulation peaks in spring–early summer. In winter, the western extension of the Siberian anticyclone predetermines sub-zero temperatures and small amounts of solid precipitation in the mountains and on the plains. In summer, the thermal Asiatic depression dominates driving advection from the south which results in hot and dry weather on the plains (Shahgedanova, 2002).

Areas of the study catchments vary between 600 and 700 km^2 for the Turgen and Osek to 40–50 km^2 for the Kishi Almaty and Teresbutak (Table 1). All selected catchments extend to over 4000 m a.s.l. Glaciers occupied 565 km^2 and 465 km^2 in the Kungei-Ile Alatau in 2008 and in Jetisu Alatau in 2011 respectively (Severskiy et al., 2016). All studied catchments, except the Teresbutak, accommodate glaciers which descend to approximately 3500 m a.s.l. The highest proportion of glacierized area of 12–15% characterised the Kishi Almaty and Ulken Almaty catchments (Tables 1 and 2). The snow and glacier melt period is limited to JJA extending to September in individual years (Fig. 11e and d further in the text). The seasonal flow cycle is driven by snow melt in June-July and glacier melt in August (Aizen et al., 1996; 1997). Summer snowfalls affect annual mass balance because they disrupt ablation but seasonal snow, falling below the ELA (positioned, on average, at 3800 m a.s.l.; Fig. 11e further in the text), melts over summer providing input to runoff (Dyurgerov et al., 1994).

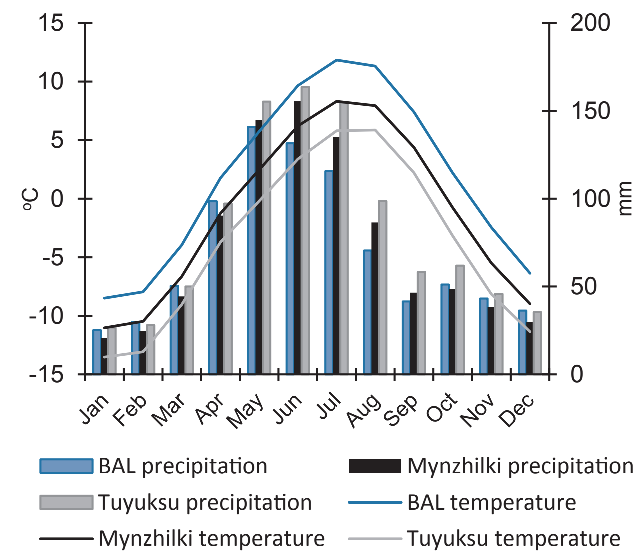

Fig. 2. Temperature and precipitation climatology for 1974–2013 for BAL (2500 m a.s.l.), Mynzhilki (3010 m a.s.l.) and Tyuksu (3438 m a.s.l.) meteorological stations. Locations of the stations are shown in Fig. 1.

5. Results

5.1. Descriptive statistics and decadal hydrographs

The hydrographs of the studied rivers were consistent with the nivo-glacial flow regime whereby maximum streamflow was observed in July–August except for the unglaciated Teresbutak catchment where the flow peaked in June in line with snow melt (Table 3; Fig. 4). The highest streamflow values characterised the Osek where JJA streamflow averaged 31 m s^{-1} followed by the Turgen and Kishi Osek while in other rivers, the JJA streamflow was an order of magnitude lower. The highest specific discharge (streamflow normalized by the upstream catchment area) characterised catchments with the highest glacierization (i.e. the Ulken Almaty and Kishi Almaty) while the Turgen and Teresbutak had the lowest specific discharge in summer (Fig. 3).

Coefficients of variation (CV), calculated for four seasons, ranged mostly between 0.2 and 0.4 reaching higher values of 0.35–0.80 for the Teresbutak which had the lowest streamflow in the sample (Table 3). The highest interannual variability characterised streamflow in the Teresbutak, Osek and Kishi Osek in MAM, reflecting the contribution of variability in seasonal snowpack to discharge, and in Teresbutak in DJF.

5.2. Long-term trends in mean seasonal and monthly flow

The main result of the analysis of the mean seasonal flow time series is that there were no negative trends in mean flow in any season at any site in the uniform assessment period of 1974–2013 (Figs. 5 and 6). The only negative value, which did not indicate a statistically significant trend, was registered in DJF in the Turgen in the extended assessment period of 1950–2013.

From the perspective of water resources, changes in streamflow in

Table 3
Mean seasonal streamflow (m s^{-1}) and coefficient of variation (CV) for the 1974–2013 period.

Season	Prohodnaya		Teresbutak		Ulken Almaty		Kishi Alamty		Turgen		Kishi Osek		Osek	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
SON	1.4	0.20	0.3	0.35	1.9	0.25	1.3	0.48	5.4	0.24	5.2	0.25	7.5	0.26
DJF	0.8	0.18	0.2	0.80	0.8	0.19	0.7	0.17	2.8	0.28	2.5	0.27	3.2	0.28
MAM	1.1	0.21	0.5	0.57	0.9	0.30	0.8	0.28	6.7	0.23	3.8	0.42	7.8	0.38
JJA	3.1	0.23	0.7	0.45	4.1	0.26	2.8	0.36	15.0	0.18	15.1	0.20	30.7	0.16

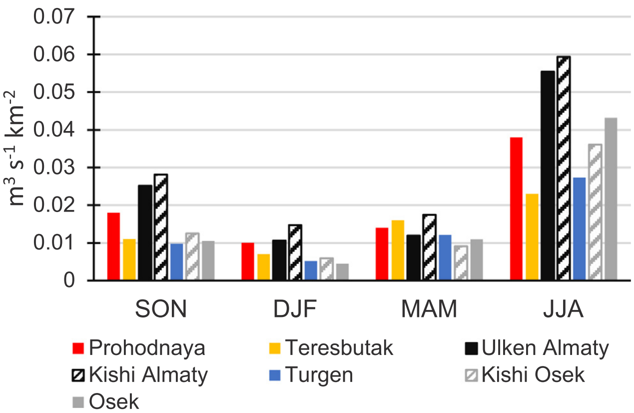

Fig. 3. Seasonal values of specific discharge (m^3 s^{-1} km^{-2}) for the 1974–2013 period.

summer and the adjacent months are most important. During the 1974–2013 period, in JJA, positive trends significant at 0.05 confidence level were observed in the mean flow of the Ulken Almaty, Kishi Almaty, Teresbutak and Turgen (where the trend was weak at 0.48% a^{-1}) while trends were not significant in the mean flow of the Prohodnaya, Osek and Kishi Osek (Fig. 6). The strongest increase of 1.6% a^{-1} characterised the Ulken Almaty flow (whose gauged catchment has the highest elevation and glacierization and yielded higher specific discharge; Tables 1 and 2; Fig. 3). Streamflow of the Ulken Almaty and Kishi Almaty increased in all summer months but the strongest growth was observed in June, a month dominated by snow melt when the strongest increase in air temperature was also registered (Sect. 5.5). Unexpectedly, in the unglacierized Teresbutak catchment (Table 1), a stronger increase in mean flow occurred in July–August when glacier melt predominates.

In SON, in the uniform assessment period, positive trends of 0.6–1.6% a^{-1} were observed in all rivers in all months and were stronger than in summer. The strongest increase was registered in the Osek and Teresbutak (Fig. 6). Decadal hydrographs show an increase in streamflow, starting in late summer–early autumn and extending into winter, since the 1990s and particularly in 2000–2013 (Fig. 4). In the Ulken Almaty, Kishi Almaty and Turgen catchments, the strongest increase in mean monthly flow was observed in September indicating the extension of high flow into early autumn (Fig. 6). In DJF, streamflow increased in most rivers except the Turgen and, similarly to SON, was highest in the Osek and Teresbutak where relative changes were greater in DJF than in other seasons (Fig. 6). However, the absolute changes, observed in winter, were small.

In MAM, positive trends in mean flow were smaller than in other seasons during the 1974–2013 period but statistically significant in all rivers except the Prohodnaya (Fig. 6). The values of trends in monthly flow in spring depend on the elevation-dependent timing of snow melt. Thus in the Kishi Almaty and Ulken Almaty high-elevation catchments, the largest increase was observed at the end of May before the peak flow is reached in June (Fig. 6). In the Teresbutak, Kishi Osek and Osek, higher trend values were registered in March and April while those in late spring–early summer were not significant. In the Turgen, April was the only spring month with a statistically significant positive trend (Fig. 6).

While 1974 was selected as a start year of the uniform assessment period to accommodate the Kishi Almaty record, the 1970s were a period of negative anomalies in river flow (Fig. 5). Sensitivity of trends to the choice of assessment period was tested by recalculating trend values using data for the full duration of individual records. The general tendency towards an increase in mean flow remained although trend values were smaller (Fig. 6). The Ulken Almaty was the only river where positive trends in JJA in the extended assessment period were significant at 0.05 confidence level (Fig. 6). Here, the positive trend values in June–September nearly doubled in 1974–2013 in comparison with 1952–2013 (Fig. 6). However, while in 1974–2013, the strongest trends were registered in June when river flow is dominated by snowmelt, in 1952–2013, a slightly stronger increase was observed in August–September when glacier and ground ice melt dominates. In SON and DJF, trends remained significant in all rivers except the Turgen. In spring, a significant increase in streamflow was registered in most catchments in March and April but not in May (Fig. 6).

Seasonal and monthly mean flow of the Turgen was most sensitive to the change of the assessment period. There were no statistically significant trends in any season although statistically significant increase in streamflow was observed in August when glacier melt peaks.

5.3. Trends in Qn flow indicators.

Trends for the seasonal Q10 to Q90 thresholds for 1974–2013 are shown in Fig. 7. Similarly to the mean flow, all significant trends were positive.

In JJA, the strongest increase occurred in the low flow thresholds (Q70 and Q90) which are considered to be an indicator of glacier and ground ice melt contribution (Collins, 1987). Positive trends in Q90 were significant in all rivers and in Q70, in all rivers except the Osek. The strongest trends were observed in the Ulken Almaty where both Q90 and Q70 were increasing at a mean rate of 1.9% a^{-1} (Fig. 7). Until the late 1970s, trend values in all quantile indicators in JJA co-varied in the Ulken Almaty, Turgen and Prohodnaya (Figs. 8 and 9). However, a very strong growth in Q90 was observed in the Ulken Almaty since the 1980s peaking in 2003–2005 as shown by Sen's slope estimator applied in 20-year moving windows (Fig. 9e). The 1952–1989 and 1990–2013 mean values of the Ulken Almaty Q90 were 1.6 m s^{-1} and 2.8 m s^{-1} respectively indicating a statistically significant step change in base flow. The contemporaneous changes in base flow were much smaller in the Turgen and Prohodnaya, whose catchments have lower glacierization. After 2005, Q90 values in the Ulken Almaty and the Kishi Almaty remained high (Fig. 8a) but they were not increasing (Fig. 9e).

Changes in the median and high flow were smaller than in the low flow indicators in JJA. The behaviour of the mean (Fig. 5) and median flow, however, was closer to that of Q10 and Q30 than Q70 and Q90 (Fig. 8a). Significant trends in Q10 were observed only in the Ulken Almaty and Teresbutak (Figs. 7 and 8). Similarly to the base flow, variability in the median and high flow indicators in JJA was consistent in the Ulken Almaty, Turgen and Prohodnaya until the last two decades of the 20th Century. More recently, positive values of the 20-year trends continued to increase in the Ulken Almaty but not in the other two

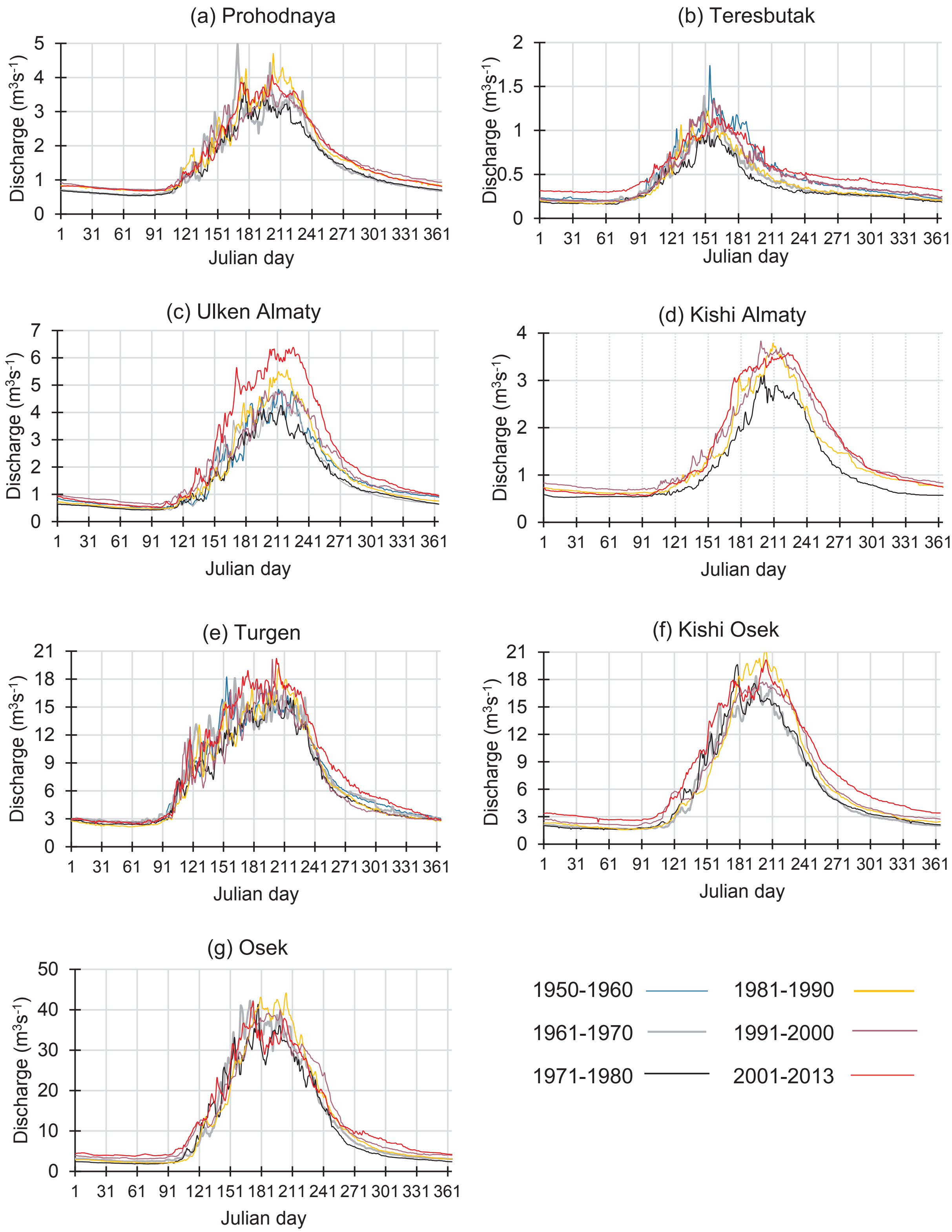

Fig. 4. Daily streamflow averaged over the approximately 10-year periods.

rivers (Fig. 9a and c).

In SON, positive trends were ubiquitous and particularly strong in the high flow thresholds reflecting an increase in September flow whose absolute values are higher than those in October–November (Fig. 4). Thus Q30 and Q10 increased at the rate of 1.1–1.5% a^{-1} and 1.7–1.9% a^{-1} respectively (Fig. 7). In the Ulken Almaty, until approximately 1990, temporal variability in all thresholds followed similar pattern (Figs. 8b and 9b, d, f). However, in the last 25 years, while growth in low and median flow slowed down, increase in high flow indicators, characterising mostly September flow, intensified similarly to JJA. The recent trends in high and median flow of the Turgen were consistent with those of the Ulken Almaty in SON in contrast to JJA.

In winter, trends in flow indicators were mostly consistent with the

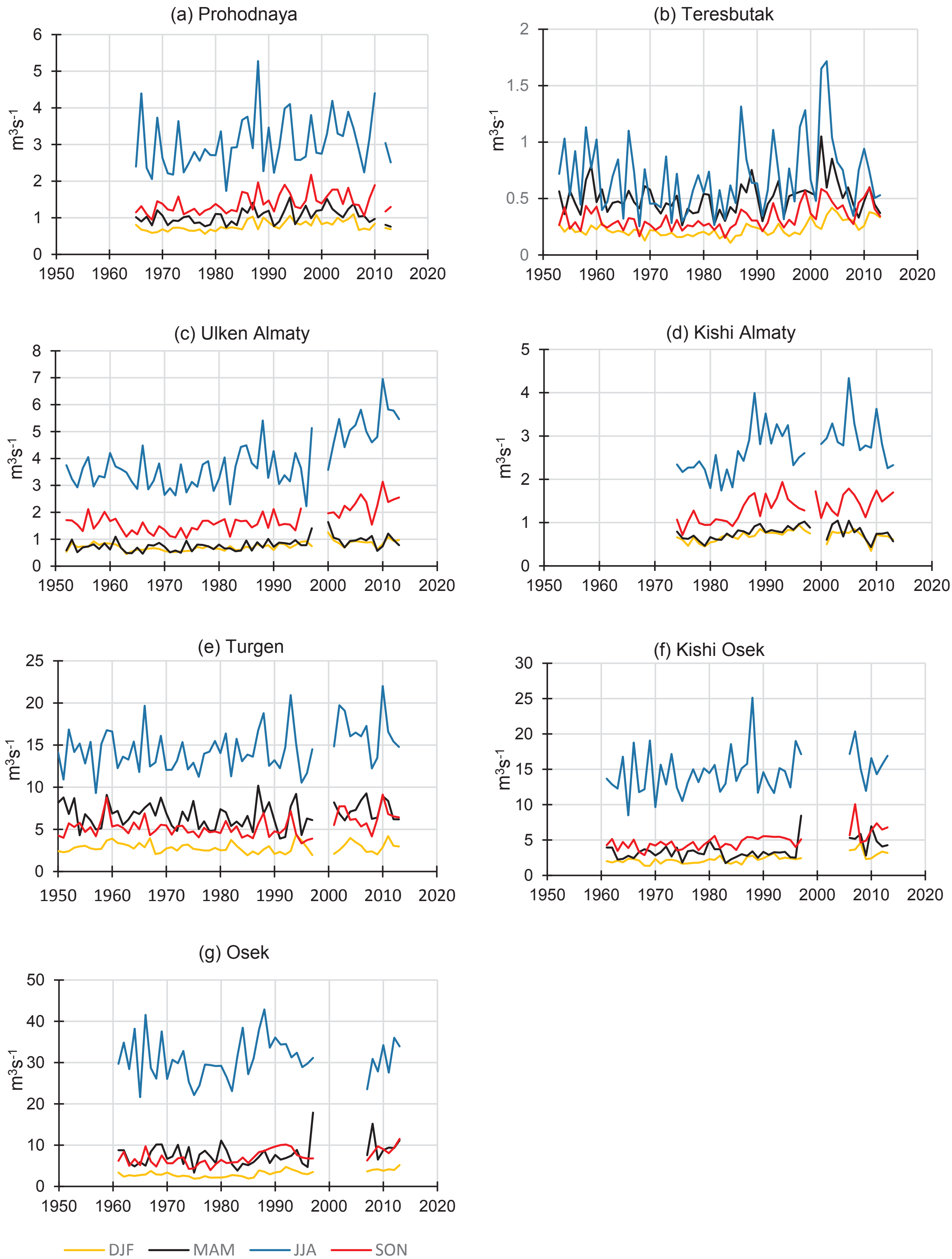

Fig. 5. Time series of seasonal mean streamflow ($m^3 s^{-1}$). Note that different scales are used for different rivers.

autumnal trends. An exception is the Turgen, where no statistically significant trends were found in any flow category. The strongest positive trends, with an increase of 1.8–2% a^{-1} in all flow categories, were observed in the Teresbutak. Trends in the spring flow were generally smaller than in other seasons (Fig. 7) although there was a strong difference between trends in Qn calculated for the individual spring months. An exception was the Osek and the Kishi Osek where positive trends observed in spring exceeded those observed in summer due to the high flow values exceeding plus two standard deviations in May 1997, 2008 and 2010, and due to a steady increase in March flow.

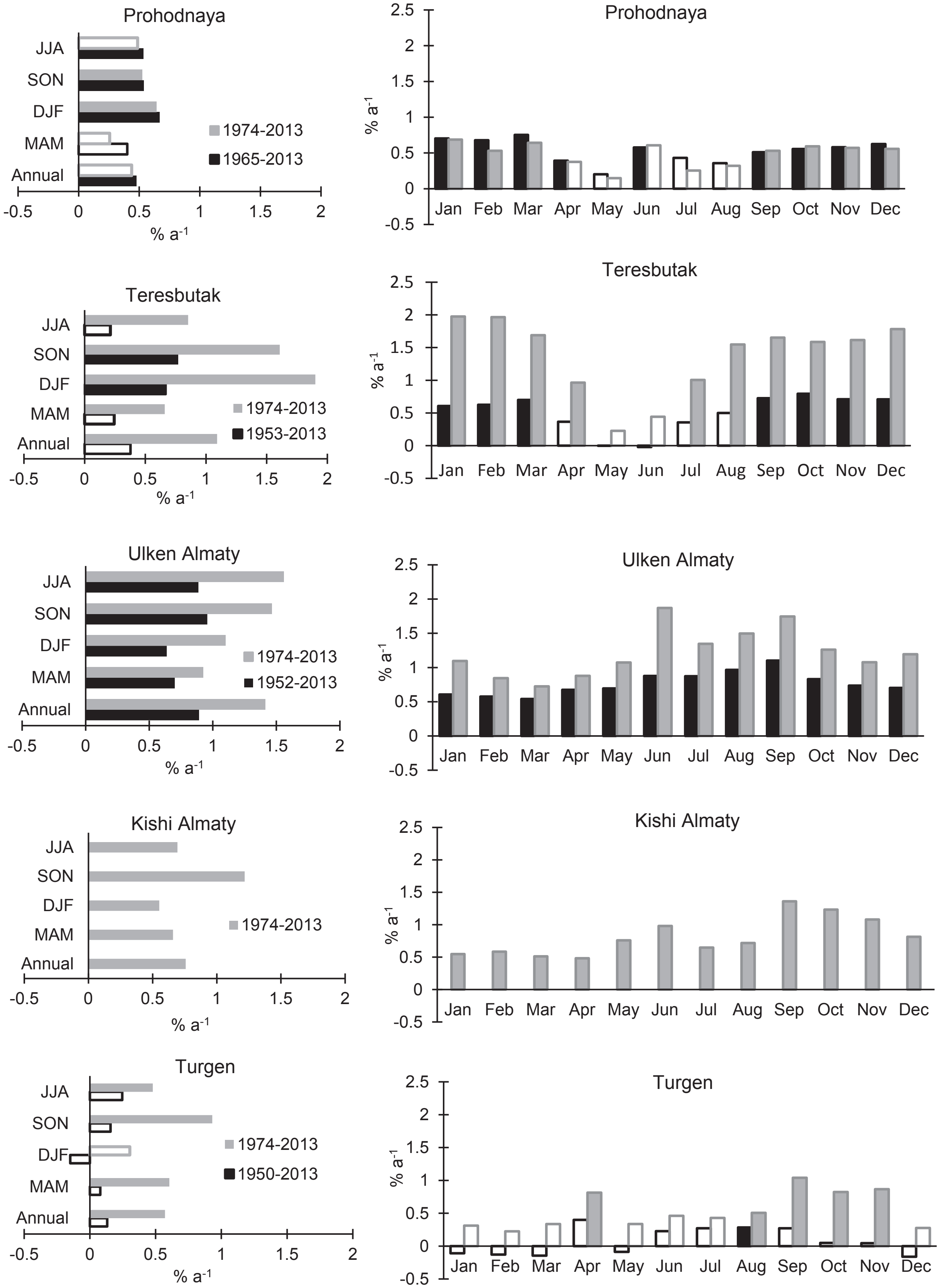

Fig. 6. Trends in seasonal and monthly streamflow (% a^{-1}) over the 1974–2013 period and full duration of individual records calculated using Mann-Kendall test. Solid bars represent trends significant at 0.05 confidence level.

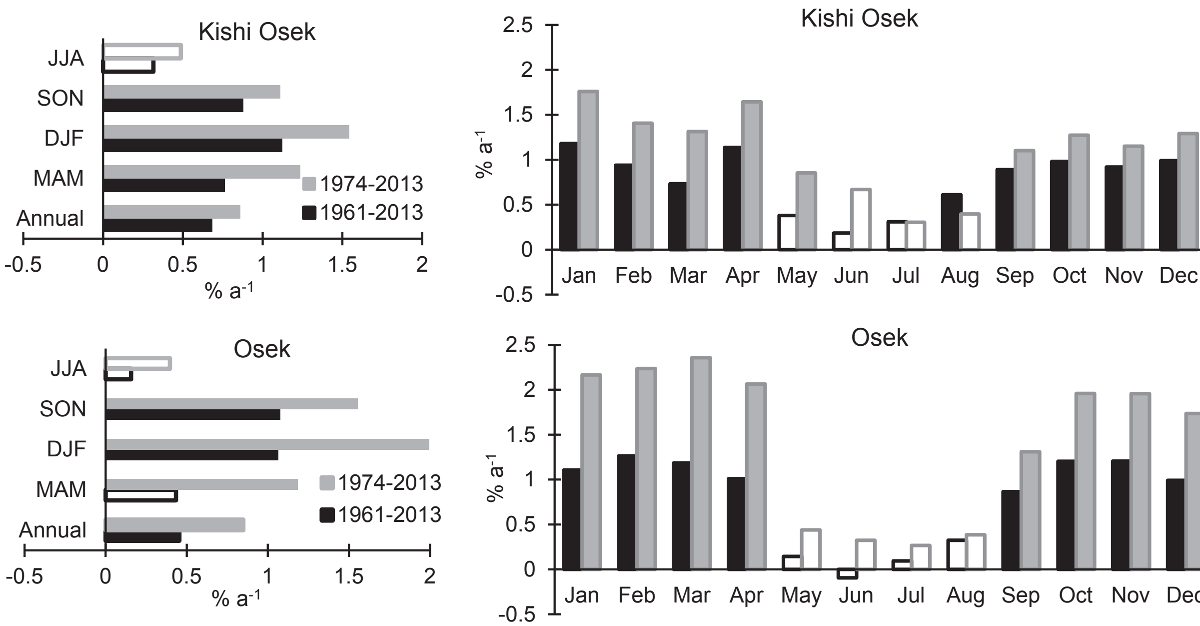

Fig. 6. (*continued*)

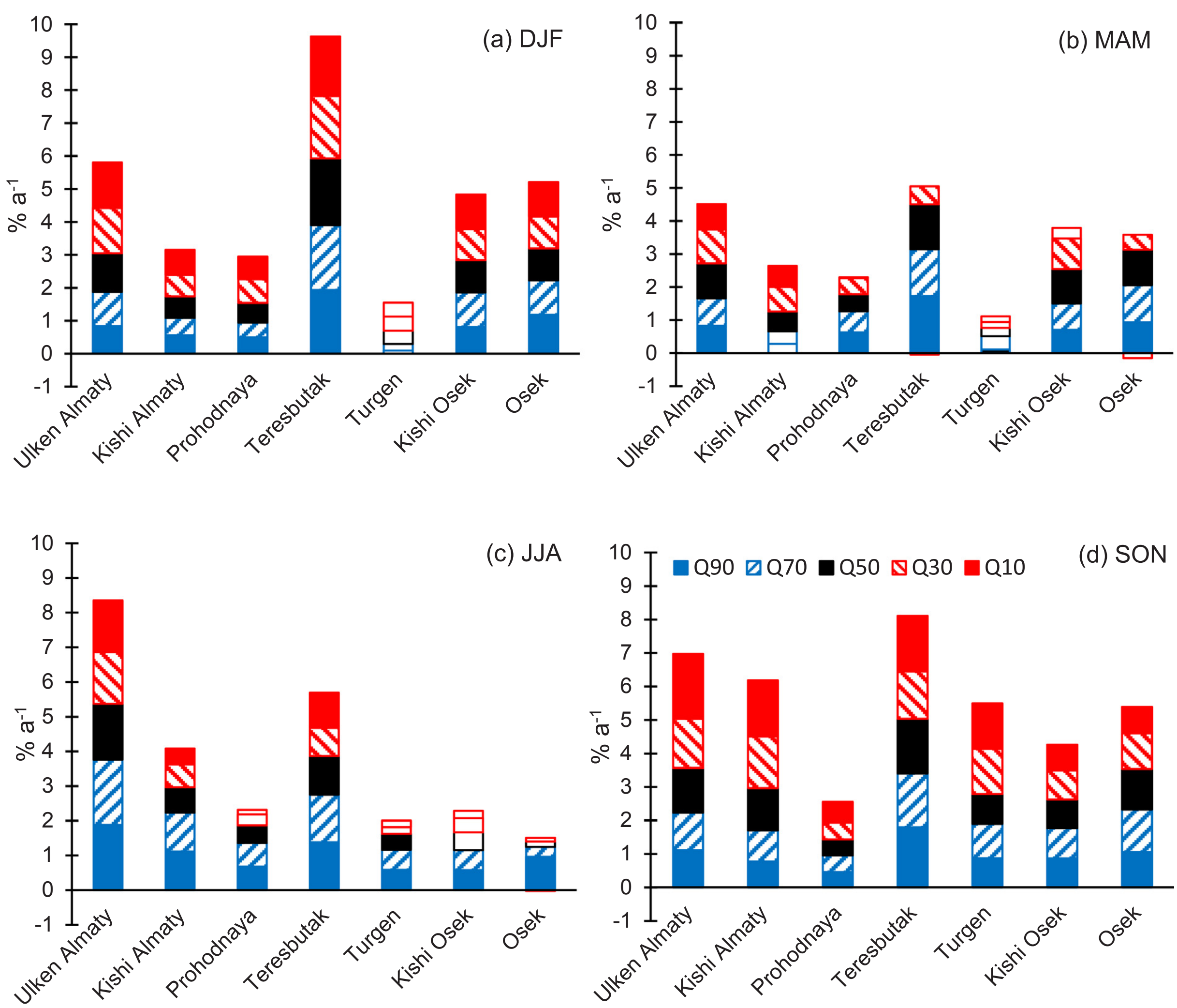

Fig. 7. Trends in seasonal streamflow (% a^{-1}) over the 1974–2013 period calculated using Mann-Kendall test for a range of thresholds. Solid bars represent trends significant at 0.05 confidence level.

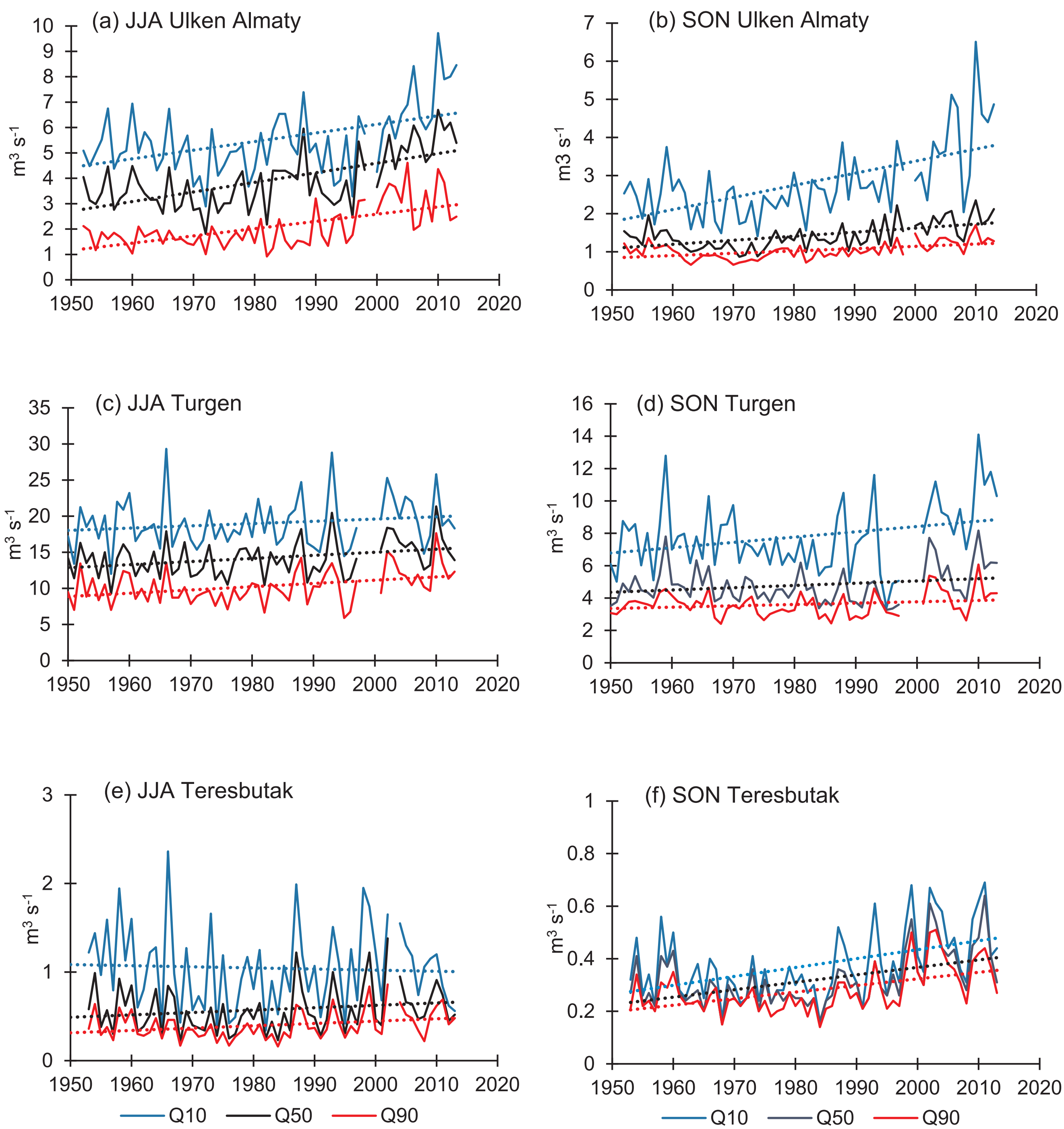

Fig. 8. Time series of Q10, Q50 and Q90 flow thresholds with linear trends (dashed straight lines) for the Ulken Almaty, Turgen and Teresbutak for JJA and SON.

5.4. Peak over threshold (POT)

POT 3 time series for the Ulken Almaty and Turgen for JJAS are shown in Fig. 10 for the 1950 (1952)-2013 period. Decadal mean frequency of POT events (average number of POT events per year in each decade) was used instead of its count because of the gaps in the time series (Table 1) and slightly uneven time steps. The mean values of POT flow were 24.0 $m\,s^{-1}$ and 6.1 $m\,s^{-1}$ for the Turgen and the Ulken Almaty records respectively. Until the 2000s, variability in the frequency of POT events was small in both rivers although a decrease in the frequency of POT events and mean POT flow values was observed in the 1970s in comparison with the earlier decades (Fig. 10b). Since the beginning of the 21st Century, the frequency of POT events and mean POT flow values increased in the Ulken Almaty but not in the Turgen. Overall, there was no long-term trend in the Turgen's POT time series. In the Ulken Almaty, trend in the POT frequency record was significant at 0.05 confidence level. In the last two decades, POT flow values were replicating the behaviour of Q10 flow (Fig. 8a and b) while in the 1950s–1960s, several large floods occurred and the POT flow values exceeded Q10 particularly in 1959, 1962 and 1965.

5.5. Trends in temperature, precipitation and glacier mass balance

Positive trends characterised spring and autumn temperatures (Fig. 11a; Table 4). At both BAL and Mynzhilki, a step change in JJA temperature occurred in the 1970s and, as a result, statistically

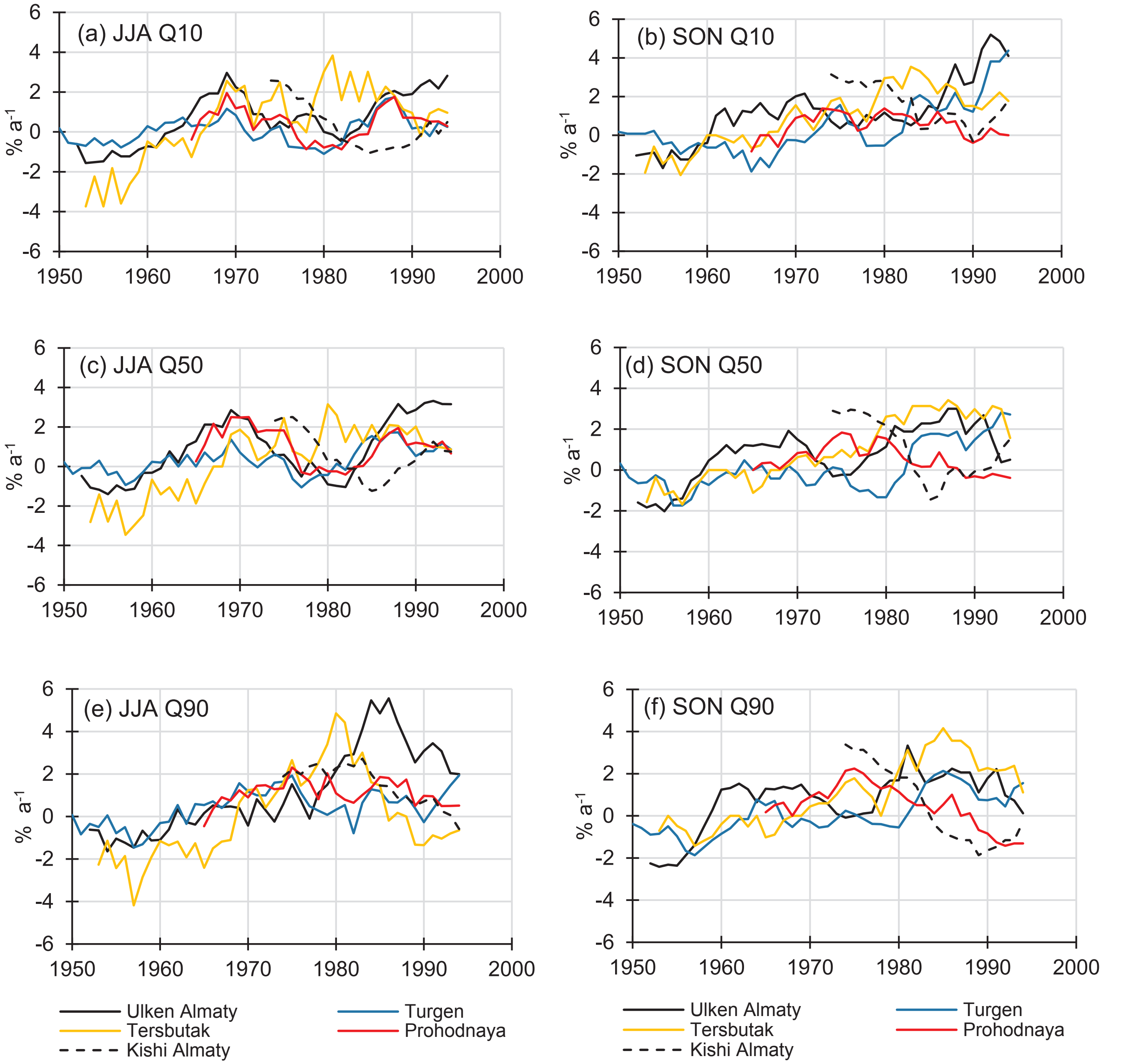

Fig. 9. Sen's slope estimator applied in 20-year moving windows and normalised by the time series' means. The values are plotted for the start of the moving window. Gaps is the data (Table 1) are not shown.

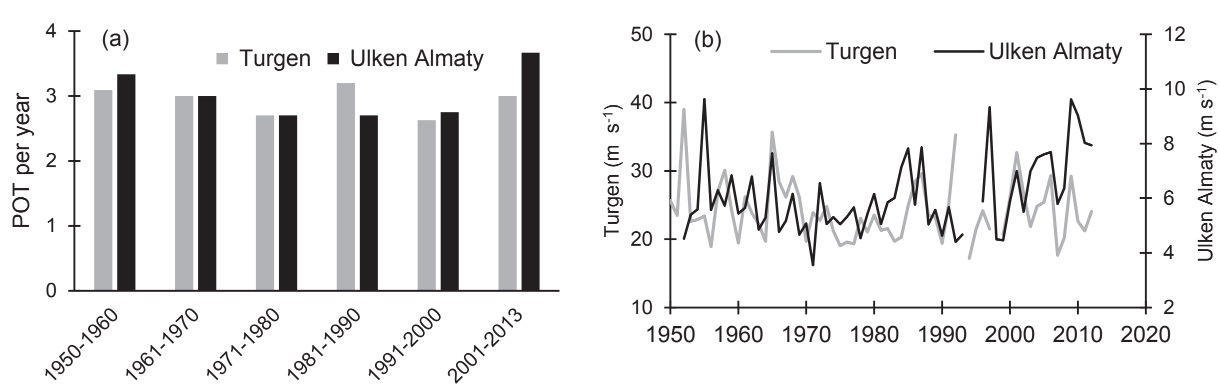

Fig. 10. (a) Peak over threshold (POT) series with an average frequency of 3 events per year for June-September (JJAS). Each bar represents decadal mean frequency of POT. The Ulken Almaty record starts in 1952 (see Table 1 for the details of missing data). (b) Mean POT flow.

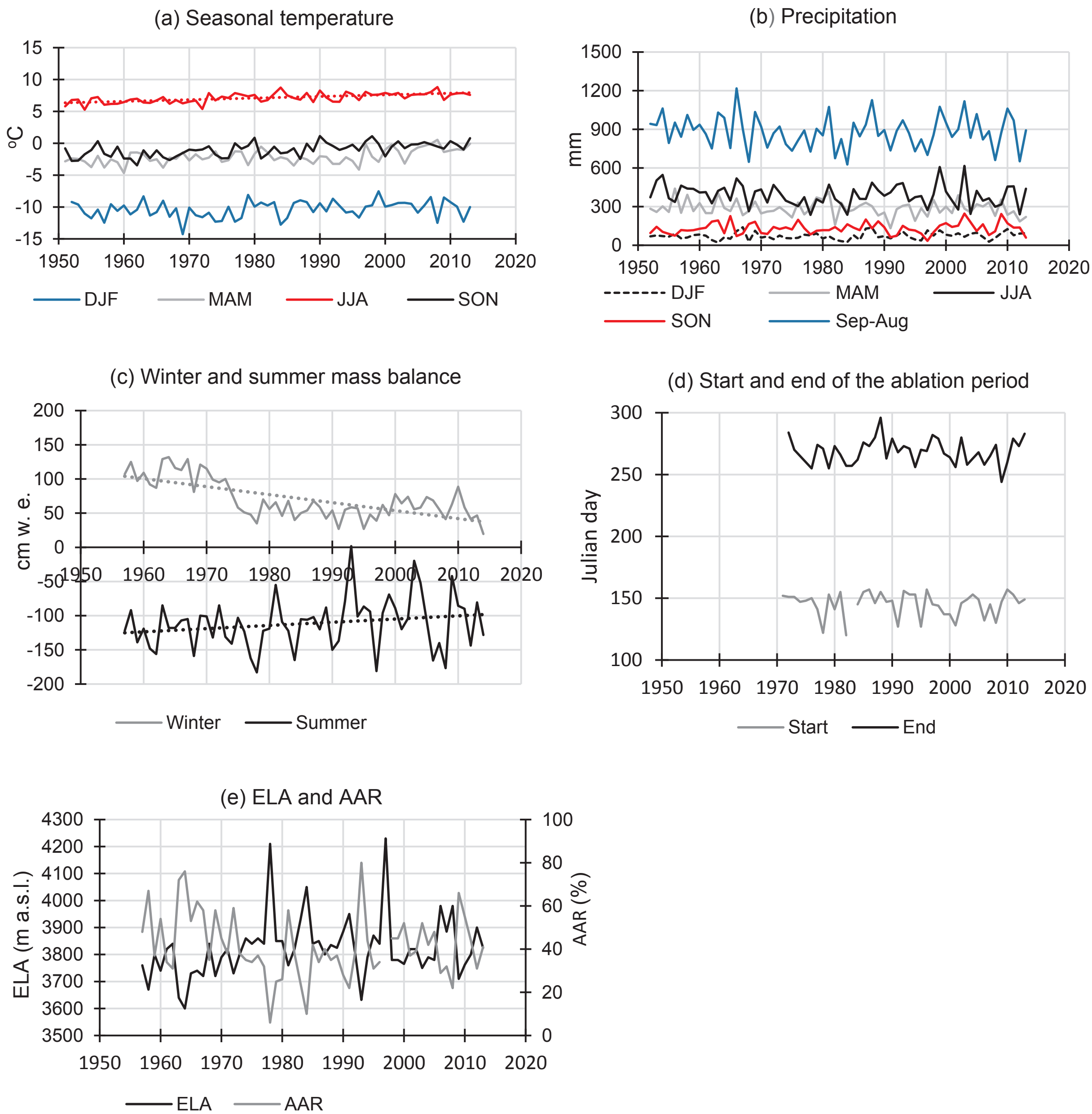

Fig. 11. Time series of (a) air temperature and (b) precipitation from the Mynzhilki meteorological station (3010 m a.s.l.); (c) winter and summer mass balance of the Tuyuksu glacier, (d) beginning and end dates of the summer balance in each year, and (e) ELA and AAR at the Tuyuksu glacier. Summer mass balance values are shown as negative while absolute values are used in Table 5. Dotted lines show linear trends in the temperature and mass balance series.

significant trends were found in the 1951–2013 record but not in the 1974–2013 record. At Mynzhilki, JJA temperatures averaged over 1951–1972 and 1973–2013 were 6.5 °C and 7.5 °C respectively (a difference significant at 0.05 confidence level). At the high-elevation Tuyuksu station, the trend in JJA temperature in the 1974–2013 period was significant at 0.07 confidence level. While an increase in autumn temperatures occurred across the Tien Shan, summer warming was reported only for the elevations exceeding approximately 2500 m a.s.l. (Unger-Shayesteh et al., 2013). In the study region, the strongest warming in summer was observed in June at all three stations possibly

Table 4
The Mann-Kendal test statistics for trends in seasonal air temperature for 1974–2013 (1951–2013) periods. Values of trends significant at 5% confidence level are highlighted in bold. Locations of the meteorological stations are shown in Fig. 1. SSE – Sen's slope estimator.

Station/Season	Bolshoe Almatinskoe Lake			Mynzhilki			Tuyuksu		
	τ	p	SSE	τ	p	SSE	τ	p	SSE
DJF	0.01 (0.05)	0.38 (0.55)	0.02 (< 0.01)	0.09 (0.17)	0.44 (0.05)	0.01 **(0.02)**	0.11	0.32	0.01
MAM	**0.33 (0.22)**	**< 0.01 (0.01)**	**0.06 (0.02)**	**0.33 (0.32)**	**0.01 (< 0.01)**	**0.05 (0.03)**	**0.32**	**< 0.01**	**0.05**
JJA	0.14 **(0.25)**	0.21 **(0.01)**	< 0.01 **(0.01)**	0.17 **(0.43)**	0.14 **(< 0.01)**	0.01 **(0.02)**	0.21	0.07	0.02
SON	**0.22 (0.32)**	**0.05 (< 0.01)**	**0.03 (0.03)**	**0.27 (0.42)**	**0.02 (< 0.01)**	**0.04 (0.04)**	**0.31**	**0.01**	**0.04**

as a result of the feedback between increasing air temperature and earlier snow melt (Pepin et al., 2015).

While strong decadal variability characterised precipitation time series in every season, there was no significant long-term trend in any of the precipitation series either in the study area (Fig. 11b) or in the northern and central Tien Shan (Kutuzov and Shahgedanova, 2009; Narama et al., 2010; Unger-Shayesteh et al., 2013). The periods of negative anomalies in precipitation were registered, most notably between 1970 and 1980 (Fig. 11b) when a strong decline in winter mass balance occurred (Fig. 11c). In 1952–1973, winter mass balance averaged 110 cm water equivalent (w.e.). In 1974–2013, it was 56 mm w.e. evidencing a significant decline in precipitation in the accumulation period at higher elevations. By contrast, there was no significant trend in summer mass balance probably because of the strong variability observed in the last two decades. An exceptionally strong summer melt, caused by the strong positive temperature anomalies, was observed in 1997 and in 2006–2008 but melt was weak in the wet summers of 1993, 2003 and 2009. Data on the duration of winter and summer mass balance seasons, available from 1971, show that there was no change in the timing of the onset and end of the melt season at the Tuyuksu glacier (Fig. 11d). This, however, does not exclude changes in the intensity of melt in the early autumn. Positioned at higher elevations, Tuyuksu may not be representative of variability in the onset of snow melt across the catchments.

5.6. Links between streamflow with air temperature, precipitation and glacier mass balance

Correlation coefficients between the original and de-trended seasonal time series of Q50 flow and air temperature, precipitation and glacier mass balance were calculated and are shown in Table 5 for two catchments with high and low glacierization and specific discharge. For three rivers with similar specific discharge (Fig. 3) – the Teresbutak, Prohodnaya and Turgen – precipitation of the preceding seasons was the main controlling factor while there was no significant correlation between streamflow and precipitation in any concurrent season. Correlations between the de-trended time series were stronger showing that interannual variability in streamflow is driven by variability in precipitation. In these catchments, correlation of JJA flow with annual (September to August) precipitation and winter mass balance of the Tuyuksu glacier (i.e. snow accumulated over the cold period) remained stationary following the anomalously dry mid-1970s (Fig. 12a and c). However, for the Ulken Almaty and Kishi Almaty, correlation between JJA flow and annual precipitation (as measured at the Mynzhilki station) declined since the 1970s whilst correlation with winter mass balance increased (Fig. 12a and c) pointing at an increasing importance of snow accumulation at higher elevations for the formation of summer discharge.

In contrast to all other catchments, air temperature (an indicator of both snow, glacier and ground ice melt) was the strongest control over the Ulken Almaty streamflow in all months (Table 5). Temperature correlated with all flow indicators in JJA, however, its correlation with median and low flow was slightly stronger (correlation coefficients of 0.65 and 0.60 for Q50 and Q90 respectively) than with high flow (0.47 for Q10). Correlations between the unmodified streamflow and temperature time series was higher than between the de-trended time series. It remained significant throughout the observation period (Fig. 12b) showing that the positive long-term trend in temperature (Table 4) drives the increase in streamflow. Correlation with summer mass balance, which is controlled in the first place by summer temperature and to a lesser extent by summer precipitation (which reduces melt; Dyurgerov et al., 1994) was weak overall but increased in the 1980s in comparison with the earlier years (Fig. 12d). In the Kishi Almaty, which is hydraulically connected to the Tuyuksu glacier, the running 20-year correlation with summer mass balance followed that of the Ulken Almaty but was weak.

Positive correlation of the Turgen and Prohodnaya JJA flow with summer temperature was weak overall but it reached statistically significant positive values in the 1970s (Fig. 12b) when summer melt extended to higher elevations as shown by the higher ELA values (Fig. 11c and e). However, after the 1970s, correlation between the Turgen summer flow and summer temperature declined and correlation with absolute values of summer mass balance reached statistically significant negative values (Fig. 12d). Correlation between the Teresbutak flow in JJA and summer mass balance was negative throughout the record showing that in this small non-glaciated catchment, flow declines in response to warm, dry weather which leads to stronger melt. The much larger Turgen now appears to respond in a similar way although glaciers still occupy 3.7% of its catchment.

A weak but statistically significant positive correlation between the Teresbutak and Turgen JJA flow and the preceding DJF air temperature can be interpreted as a contribution of accumulated snow to discharge.

Table 5
Pearson correlation coefficients between the non-transformed and de-trended (in parentheses) seasonal Q50 flow, air temperature and precipitation from the Mynzhilki station and the absolute values of seasonal mass balance for the Tuyuksu glacier for the duration of the streamflow (Table 1) or the mass balance records. Correlation coefficients significant at 0.05 confidence level are highlighted in bold.

Variable	Temperature					Precipitation				Mass balance	
Time lag	0	−3	−6	−9	−12	1–3	1–6	1–9	1–12	Summer	Winter
Ulken Almaty											
SON	**0.49** (0.25)	**0.44** (0.15)	**0.41** (0.14)	0.25 (0.17)	0.25 (−0.06)	0.001 (−0.10)	0.01 (0.08)	0.03 (0.15)	0.11 (0.22)	−0.14 (0.01)	**−0.33** (0.21)
DJF	0.01 (−0.11)	**0.32** (0.08)	**0.35** (0.08)	0.13 (−0.13)	0.03 (−0.10)	0.18 (0.11)	0.03 (−0.07)	0.18 (0.22)	0.09 (0.16)	−0.05 (0.08)	**−0.33** (0.04)
MAM	**0.35** (0.11)	0.13 (0.03)	**0.33** (0.07)	**0.32** (−0.01)	0.01 **(−0.33)**	−0.22 (−0.16)	−0.12 (−0.09)	−0.10 (−0.12)	0.09 (0.19)	−0.00 (0.14)	**−0.39** (−0.06)
JJA	**0.62 (0.40)**	**0.52 (0.31)**	0.25 (0.17)	**0.28** (−0.05)	**0.27** (0.16)	−0.17 (−0.07)	−0.09 (0.08)	0.01 (0.16)	0.15 **(0.28)**	0.06 (0.26)	**−0.30** (0.22)
Turgen											
SON	0.13 (0.02)	−0.09 **(−0.26)**	0.15 (0.07)	0.23 (0.20)	0.08 (−0.02)	0.19 (0.17)	**0.38 (0.41)**	**0.41 (0.46)**	**0.47 (0.51)**	**−0.35 (−0.32)**	0.24 **(0.51)**
DJF	−0.05 (−0.04)	−0.11 (−0.10)	−0.23 (−0.25)	−0.09 (−0.07)	−0.03 (−0.01)	0.03 (0.04)	0.07 (0.08)	**0.35 (0.35)**	**0.38 (0.38)**	−0.15 (−0.17)	0.20 (0.21)
MAM	0.02 (−0.01)	0.04 (0.03)	−0.01 (−0.05)	−0.07 (−0.14)	−0.12 (−0.17)	0.04 (0.05)	0.12 (0.12)	**0.26 (0.26)**	**0.38 (0.40)**	−0.17 (−0.17)	0.15 (0.20)
JJA	0.22 (0.05)	0.15 (0.00)	**0.34 (0.30)**	0.19 (0.04)	−0.05 **(−0.32)**	0.23 (0.31)	**0.37 (0.49)**	**0.47 (0.58)**	**0.57 (0.65)**	**−0.29** −(0.23)	0.02 **(0.38)**

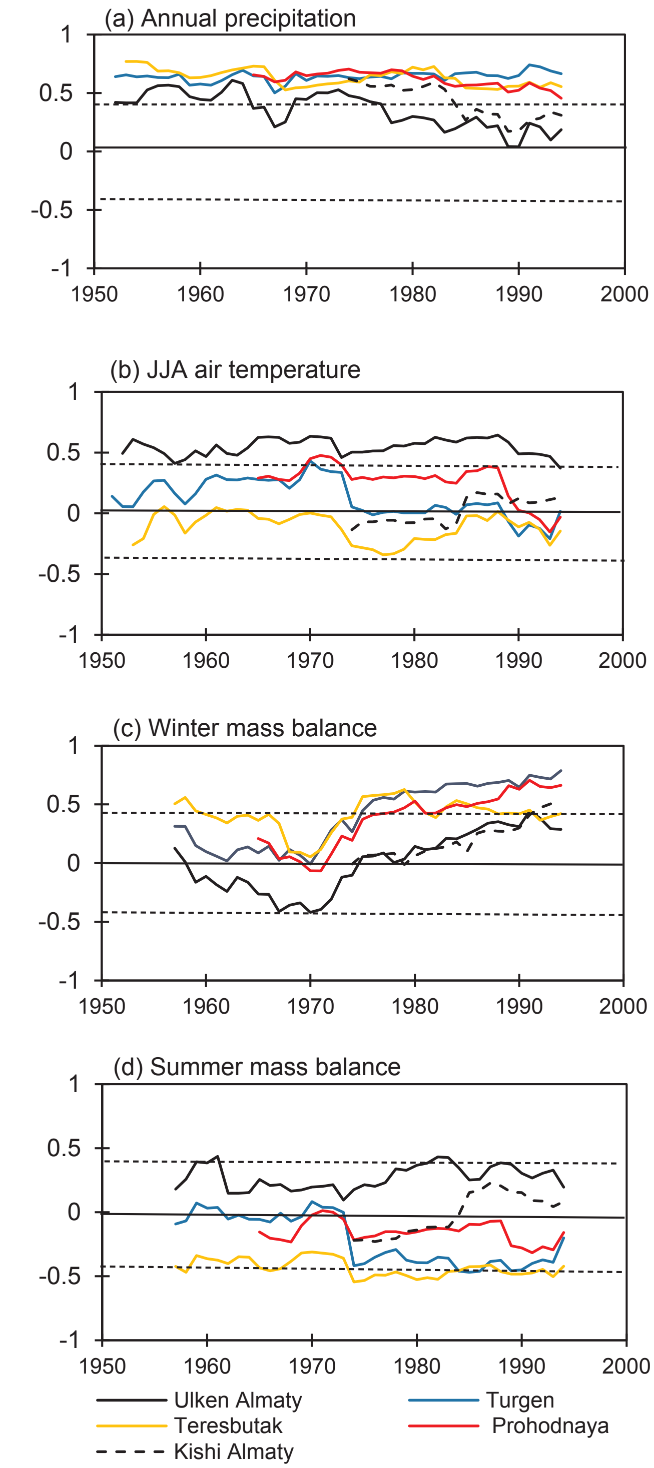

Fig. 12. Pearson correlation coefficient applied in 20-year moving windows to Q50 flow versus: (a) annual (September to August) precipitation; (b) JJA air temperature; and absolute values of (c) winter mass balance and (d) summer mass balance. The values are plotted for the start of the moving window. Straight solid and dashed black lines show zero values and values of correlation coefficients significant at 0.05 confidence level respectively. Gaps is the data (Table 1) are not shown.

In the northern Tien Shan, winter precipitation (which always falls as snow) correlates negatively with temperature because the domination of the Siberian high (westerly flow) results in low (high) temperatures and precipitation (Panagiotopoulos et al., 2005). In autumn, correlations with temperature were significant for most rivers and stronger for the high flow indicators, representing September flow, which increased in all catchments (Figs. 4 and 5). Both SON and DJF flow in the Ulken Almaty and the Prohodnaya exhibited significant correlations with temperature of the preceding seasons.

6. Discussion

6.1. Data quality relevant to the development of a reference data set

A new data set of daily streamflow measurements, starting between 1950 and 1974 and continuing at present, has been compiled for seven undisturbed catchments located in the Ile Alatau and Jetisu Alatau. The gaps in the data, resulting from the disruption of measurements in the 1990s across Central Asia, are much shorter in the selected catchments in the Ile Alatau than elsewhere (Table 1). Measurements in the Teresbutak and Prohodnaya catchments were not affected and here, the short gaps were due to floods. In the Ulken Almaty and Kishi Almaty catchments, gaps in the data were limited to approximately six months in 1998 and 1999 but there were over two years of missing data in the Turgen. There was more missing data in the Osek and Kishi Osek records (Table 1) and it might have affected the significance of the detected trends.

The in-filling of the data gaps was complicated by the fact that they affected a wide area and that the potential 'donor gauges' are located on the rivers with different characteristics and responses. The preliminary results from modelling using the HBV-ETH hydrological model showed that it can be used for the reconstruction of mean flow in the Ile Alatau in the future (Shahgedanova et al., 2016). The in-filling of the gaps in the records from the Jetisu Alatau will be more problematic because of the paucity of meteorological data.

Concerns were raised by KazHydroMet about the suitability of the Prohodnaya time series for the analysis of long-term trends (Sect. 2.3). Although trends in the mean flow of the Prohodnaya were smaller than in the neighbouring rivers (Figs. 6 and 7), they were consistent with those in a larger Turgen catchment where glaciers occupy a similar proportion of the catchment area (Table 1). Potential uncertainty about the high flow indicators in the Ulken Almaty was a concern (Sect. 2.3). However, although Q10 values in the Ulken Almaty increased more than in other catchments particularly in JJA (Figs. 7 and 8), its behaviour was consistent with other flow indicators of the Ulken Almaty as well as catchment characteristics.

On the basis of data quality and continuity, we recommend that the [near] homogeneous streamflow data from the Ulken Almaty, Turgen and [with caution] Prohodnaya can be used as a reference data set typifying catchments with diverse characteristics (glacierization, catchment elevation, specific discharge) in the northern Tien Shan. A shortcoming of this data set is a close proximity of the catchments, particularly the Ulken Almaty and the Prohodnaya. However, in the Tien Shan (Sects. 4 and 5.2; Kriegel et al., 2013; Duethmann et al., 2015) as well as other glacierized mountain regions (e.g. Birsan et al., 2005; Kormann et al., 2015), catchment elevation and glacierization appear to be more important controls over discharge than regional climatic variations. It is envisaged that continuing measurements in the Osek and Kishi Osek catchments will result in the diminishing impact of the missing data and these records will be a part of the reference data set expanding its spatial coverage.

The Teresbutak and the Kishi Almaty catchments are small (Table 1) and as such, they may not characterise regional hydrological conditions and fail to meet the requirements for the reference catchments (Burn et al., 2012; Whitfield et al., 2012). In particular, the Teresbutak, which has the smallest catchment and does not experience the moderating effect of glacier melt on discharge, shows a strong response to climatic variability (Figs. 5b, 8e and f; Table 3) and the largest long-term trends (Fig. 6) in comparison with other catchments. Rather than characterising regional change, the Kishi Almaty and Teresbutak represent responses of small catchments with contrasting characteristics to climate

change and variability. Accommodating three meteorological stations, four streamflow gauges, one of the WGMS reference glaciers and several glacier lake monitoring sites, the Kishi Almaty is the best instrumented catchment in the northern Tien Shan and the homogeneous streamflow record presented here is an important part of a wider environmental monitoring programme.

6.2. Sensitivity of trends to the selection of assessment period

Selection of assessment period can affect the values of climatic and streamflow trends (Unger-Shayesteh et al., 2013). In this study, 1974 (when there were no strong anomalies in temperature and precipitation) was selected as the starting point of a consistent period in order to include the Kishi Almaty catchment. The hydrological network expanded in Central Asia in the 1970s–1980s and relatively few sites provide longer time series. However, the same period was characterised by negative precipitation anomalies, a step change towards lower winter mass balance, and higher JJA temperatures (Fig. 11; Table 4). Trends in streamflow in 1974–2013 were much stronger than those observed since the 1950s. However, trend signs were consistent between the two assessment periods. In both periods, an increase in streamflow was observed in the cold season between September and March while changes in JJA flow varied between catchments depending on the elevation of the gauging sites and glacierization of catchments (Fig. 6). This shows that shorter data sets, starting in the 1970s-early 1980s, can be used in assessments of the long-term trends.

6.3. Trends in streamflow and their responses to climatic oscillations

The observed changes could be driven by the long-term climatic trends and responses of the cryosphere, and by short-term climatic variability (Birsan et al., 2005; Duethmann et al., 2015; Kormann et al., 2015). In the study area, the importance of these drivers depended on season, elevation and glacierization of the catchments.

6.3.1. The cold season

One of the main findings of this study is an increase in streamflow registered (i) in all autumn months in all catchments and (ii) in winter in all catchments except the Turgen (Figs. 6 and 7). Similar trends were reported by Kriegel et al (2013) for the Naryn basin but overall, changes in discharge, observed in cold season, received little attention because they are small in absolute terms and do not directly impact water availability for irrigation. Yet, these changes are important because of the potential impacts on reservoir management and recharge of aquifers (Liljedahl et al., 2017).

In autumn, the observed increase in temperature and the delayed transition to solid precipitation resulted in a strong increase in streamflow particularly in September–October (Fig. 6). There was a statistically significant correlation between the unmodified SON streamflow of all rivers except the Turgen and temperature time series but not between the de-trended time series. It suggests that climatic warming drives the observed long-term increase in streamflow.

It was previously suggested that the extension of glacier melt season may be responsible for increasing discharge (Narama et al., 2010; Kriegel et al., 2013; Pieczonka and Bolch, 2015) but this assumption was not supported with data. At the Tuyuksu glacier, the duration of melt season has not changed since the 1970s (Fig. 11d; earlier data were not available). However, in the regions with the sub-zero autumn temperatures and occurrence of permafrost, climatic warming implies potentially longer periods of ground ice melt and later freezing of soil both of which could contribute to an increase in streamflow (Yang et al., 2002; Jacques and Sauchyn, 2009).

The short-term variability in precipitation affected discharge as shown by the statistically significant correlation between the de-trended time series of precipitation and streamflow of all rivers except the Ulken Almaty (Table 5). The 20-year moving window analysis of Sen's slope of streamflow indicators showed that trend values in SON discharge (Fig. 9) are consistent with variability in precipitation (Fig. 11b).

Positive trends in mean flow and *Qn* indicators were registered in DJF and in March in all catchments except the Turgen (Figs. 6 and 7a). In these months, temperatures remain below freezing even at low elevations. In the Ulken Almaty and Prohodnaya, there was a weak correlation between the median streamflow and temperature of the preceding autumn and summer suggesting that the observed increase in discharge during the cold season could be driven by summer meltwater and by an increase in the fraction of liquid precipitation in the early autumn. Liljedahl et al. (2017) reported a positive trend in winter discharge for the lowland sectors of glacierized catchments in Alaska attributing it to increase in ground-water levels and aquifer storage fed by glacier and permafrost melt. Jacques and Sauchyn (2009) reported an increase in winter base flow in the Canadian Northern Territories attributing it primarily to summer permafrost thawing and ground-water storage. Data on ground-water levels were not available to us. It requires investigation if, in the absence of other sources of water, the same mechanisms are responsible for the observed increase in winter base flow and, perhaps more importantly, how glacier and permafrost melt affect ground-water resources in the northern Tien Shan.

In contrast to autumn, winter and early spring, trends in streamflow in April and May were inconsistent between the catchments and there was no clear elevation-dependent pattern. Trends were larger in the catchments with lower mean and gauging site elevations, i.e. the Osek and Kishi Osek but not in the Turgen (Figs. 4 and 6). The observed increase in spring temperatures (Table 4) suggests earlier snow melt but these changes as well as dates of transition from solid to liquid precipitation, which peaks in spring in the northern Tien Shan (Fig. 2), and hydrological effects of weather patterns (Kormann et al, 2015) require further investigation.

6.3.2. Summer

In JJA (a season, that is most important with regard to water resources), changes in streamflow depended on the elevation and glacierization of catchments (Fig. 6). Positive trends in mean streamflow were observed in the headwater catchments where glacierization and specific discharge were higher, i.e. the Ulken Almaty and Kishi Almaty. In the Ulken Almaty, where glaciers occupy 15% of the gauged catchment area, positive trends in streamflow were considerably larger than elsewhere (Figs. 6 and 7c). In contrast to other catchments, they were controlled by the long-term trends and interannual variability in JJA and MAM temperatures (Table 5; Fig. 12b).

In the other catchments, trends in JJA mean and median streamflow were either weaker or not significant at 0.05 confidence level (Figs. 6 and 7c). However, in all catchments, Q90 and Q70 exhibited significant growth (Fig. 7c) and temperature correlation with Q90 was higher than with Q50. A similar increase in summer base flow has been reported for other glacierized regions, including the Himalayas (Collins, 1987) and the Swiss Alps (Birsan et al., 2005) and attributed to glacier ice melt. In the study region, correlation between JJA flow and the absolute values of summer mass balance (an indicator of glacier melt) was weak and inconsistent between catchments and time periods (Fig. 12d). In contrast to the summer base flow, there was no statistically significant trend in summer mass balance of the Tuyuksu glacier (Fig. 11c). A decrease in annual mass balance, observed since the early 1970s, was driven by a reduction in accumulation which was reported for other glaciers in the Tien Shan and attributed to changes in atmospheric circulation (Cao, 1998).

In the Teresbutak, where summer flow is driven by precipitation, correlation between the median streamflow and summer mass balance was negative because summer precipitation coincides with lower temperatures and glacier melt (Fig. 12d). In the Turgen, negative correlation between streamflow and summer mass balance was established after the warm and dry 1970s (Fig. 12d). This change may be an

indicator of diminishing contribution of glacier melt to the Turgen discharge. Since the 1950s, glaciers lost 36–51% of their area in the study region (Table 2). The repeated *in situ* geodetic mass balance measurements showed that 20% of glacier volume was lost between 1958 and 1998 contributing to runoff (Severskiy, 2007). Specifically in the Turgen catchment, glaciers lost 15.2 km^2 or 42.6% of their area (Table 2). However, the observed decline in glacierized area was small relative to the total catchment area. Glaciers occupied 5.6%, 4.6% and 3.7% of the gauged Turgen catchment in 1974, 1990 and 2008 respectively and the ability of such a reduction in glacierization to alter nourishment regime requires further investigation using modelling.

The loss of glacierized area, contributing to discharge, was partly compensated by the production of liquid runoff at higher elevations (Dyurgerov et al., 1994). The ELA increased from 3750 m in 1957–1972 to 3850 in 1973–2013 at the Tuyuksu glacier (Fig. 11e) and an average increase in ELA of 23 m in 1973–2003 was reported for the Tien Shan (Aizen, 2011). A step reduction in the AAR from 52% in 1957–1972 to 38% in 1973–2013 was registered at the Tuyuksu glacier (Fig. 11e).

In catchments with lower glacierization, precipitation in the preceding (snow accumulation) season was the main control over JJA streamflow with stronger links between the de-trended streamflow and precipitation time series (Table 5). This correlation remained both stable and statistically significant throughout the extended assessment period in the Turgen, Prohodnaya and Teresbutak (Fig. 12a). In the Ulken Almaty and Kishi Almaty catchments, correlation between streamflow and precipitation, both annual and that of cold season, declined since the mid-1970s (Fig. 12a) while correlation with winter mass balance, representing the accumulated cold-season precipitation, changed from negative in the 1970s to positive after the 1990s (Fig. 12c). This discrepancy is difficult to explain. During this time, there was no increase in winter mass balance (Fig. 11c) and there is nothing to indicate that trends in precipitation at higher elevations were different from those at Mynzhilki (Fig. 11b). The observed increase in ELA (Fig. 11e) and the expansion of area of liquid runoff could potentially explain the increasing correlation between JJA streamflow and winter mass balance. However, correlation between the Ulken Almaty and Kishi Almaty JJA streamflow records and ELA was not significant at 0.05 level.

An increase in JJA flow in the higher-elevation catchments where glaciers occupy more than 10% of the total area, registered in this study, in other regions of Central Asia (e.g. Kriegel et al., 2013; Duethmann et al., 2015) and world-wide (e.g. Birsan et al., 2005), suggests that this is an approximate threshold over which glaciers make a stronger impact on summer mean and median streamflow than variability in precipitation. However, we note that in the catchments with lower glacierization, e.g. the Turgen and Kishi Osek, positive trends in streamflow were observed in August, a month dominated specifically by glacier melt. The low flow indicators (Q90 and Q70), representative of glacier and ground ice melt (Collins, 1987), increased in all catchments (Fig. 7) pointing at the increasing contribution of these sources to discharge.

In this analysis, we did not consider changes in evaporation because of the lack of the direct long-term measurements of evapotranspiration and variables required for its calculation. The estimations based Turc's method, in which temperature from the Mynzhilki station was used (Vilesov et al., 2013), suggested that changes in evaporation at higher elevations were small and unlikely to affect streamflow to a significant extent. This requires further investigation focusing on the potential effects of solar radiation and wind speed (Yang et al., 2014) and changes in evapotranspiration at lower elevations where they may be stronger.

6.4. *Considerations of changes in the ground ice*

The melt of rock glaciers and permafrost is an important factor affecting discharge and their potential impacts on the winter flow and on the low flow indicators in summer were addressed in Sect. 6.3. In the Kishi Almaty and Ulken Almaty catchments, rock glaciers containing significant amount of ice, occupied 0.47 km^2 and 4.77 km^2 (just under 30% of the glacierized area) respectively in 1999. Recently, their movement accelerated indicating their increasing melt (Bolch and Marchenko, 2006). Our field observations in 2015–2017 confirmed a considerable discharge from the rock glaciers in both catchments and particularly in the Ulken Almaty.

Modelling showed that the area of permafrost distribution in the Ulken Almaty and Kishi Almaty catchments declined by approximately 20% and its lower boundary shifted 150–200 m upward in the last 125 years (Marchenko et al., 2007). Measurements showed that permafrost temperatures increased by 0.3–0.6 °C and the depth of active layer declined by 23% since the 1970s. These changes undoubtedly contributed to increasing streamflow and especially to the low flow indicators which showed the strongest growth in summer (Fig. 7).

7. Conclusions

For the first time in several decades, a full range of flow indicators, derived from a homogeneous daily streamflow data set from seven undisturbed catchments in the Tien Shan, has been analysed, providing insights into the factors controlling changes in discharge and implications for water resources and hazard management. The main findings are as follows:

(i) Despite the observed reduction in glacier area of 36–50%, there was no reduction in streamflow in any catchment or season in the northern Tien Shan since the 1950s;
(ii) In summer, streamflow increased in the catchments with higher elevation and glacierization of over 10%; in the lower-elevation catchments, this increase was limited to the consistent 1974–2013 period but there was no significant change in the longer time series of the mean and median streamflow;
(iii) In summer, a stronger increase was observed in the low flow indicators associated with glacier and permafrost melt in all catchments;
(iv) In autumn and winter, streamflow increased across the region and the high flow indicators exhibited the largest growth due to the prolongation of the high flow period into September; in relative terms, this increase was stronger than in other seasons.

From the perspective of water resources, the key finding is the absence of negative trends in streamflow overall and, particularly, in summer. To date, the observed glacier retreat has not resulted in diminishing flow. By contrast, a strong growth in summer discharge, driven by increasing temperature, was registered in the most heavily glacierized Ulken Almaty catchment (supplying water to Almaty city) where the proportion of glacierized area declined from 30% in the 1950s to 16% at present. This increase in streamflow could be sustained by liquid runoff from higher elevations and, importantly, by the meltwater from rock glaciers and permafrost.

We conclude that there are no immediate problems with water availability in the northern Tien Shan in the undisturbed catchments although flow reduction cannot be ruled out under the warmer climate in the future. A post-1970s increase in summer streamflow and extension of high flow into September will improve hydropower capacity and reduce pressure on the groundwater. It is possible that it is the replenished ground-water resources that sustained the observed increase in winter base flow in the study region. However, an increase in high flow and POT frequency in the more heavily glacierized catchments indicate that investments in hazard management will be required in the headwater regions.

Declaration of interests

None.

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Authors' Contribution

Shahgedanova designed the study, supervised compilation of the data archive, contributed to data analysis, wrote the paper; Afzal led data processing and analysis, contributed to the compilation of the archive and writing the paper; Severskiy contributed to designing the study and writing the paper; Usmanova, Saidaliyeva, Kapitsa and Kasatkin contributed to the compilation of the archive and data processing and analysis; Dolgikh assisted with the compilation of the data archive.

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